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THE TECHNICAL COLLEGE SERIES

PRODUCTION ENGINEERING

FOR HIGHER NATIONAL CERTIFICATE

I—MACHINE TOOLS

By

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GENERAL EDITOR'S FOREWORD

THE TECHNICAL COLLEGE SERIES today includes many books which are outstanding in their particular fields, and it is the aim of the publishers to maintain and develop the worthy tradition of the Series while meeting in full the increasing needs of technical and scientific education.

An outstanding contribution of the technical colleges to education has been the system of National Certificates under which the Ministry of Education and the colleges work in association with leading professional institutions. The system has progressed from its early preoccupation with engineering until the schemes now cover practically the whole field of higher technology and applied science. The major engineering institutions, the Royal Institute of Chemistry, the Institute of Physics, the Institution of Metallurgists, are all associated with National Certificate schemes. There are National Certificates in Building and in Commerce, with each of which a group of professional institutions is associated. Though the pattern of National Certificate Courses was originally dictated by the needs and limitations of the evening student, the system of endorsements obtainable by further study has now brought about the result that these courses have been extended to meet the full requirements of practice in the subjects with which they deal. During recent years the system of part-time-day release of apprentices and learners has become common in all branches of industry as well as in the public services. This has effected something like a revolution in technical education; and in particular the treatment of National Certificate studies up to the standard already indicated has become much broader.

The books included in the Series will be planned to suit the requirements of three main groups: (i) the part-time and full-time students working in technical colleges for professional qualifications and university degrees; (ii) technologists, managers, and research workers in industry; (iii) teachers in technical colleges and elsewhere who require text-books of high standard, but broad enough in the treatment of their subjects to be readily adaptable to local approved schemes of study.

W. E. FISHER

FOREWORD

FROM the year 1939 onwards considerable attention and impetus have been given to the subject of Production Engineering, and in 1941 the Board of Education issued a Syllabus in connection with the Arrangement of Courses for Higher National Certificates in Production Engineering. This syllabus contained the recommendations of the Joint Committee of the Institution of Mechanical Engineers, the Institution of Production Engineers, and the Board of Education for the Basic Course A I year and Advanced Course A II year.

The subject of Machine Tools is included in both years A I and A II, and whilst the present book is primarily intended to cover the work called for in the above Syllabus for Higher National Certificate Courses in Production Engineering, it also covers ground which will be useful for students taking City and Guilds Courses in Machine Shop Engineering, and work on Production Engineering Questions of the Union of Lancashire and Cheshire Institutes.

It is hoped that the presentation of this subject will be such that it will also be of use to those engaged in Production Engineering, such as draughtsmen in Jig and Tool Drawing Offices, students taking endorsements to Existing National Certificates, and some sections of Production Planning Departments.

The author acknowledges the permission which has been kindly given by Messrs. Longmans, Green, & Co. Ltd., to reproduce the Logarithmic Tables, which are taken from Mr. P. Abbott's *Mathematical Tables and Formulae*.

R. DENT

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CHAPTER I

PLANNING AND OPERATION CHARTS

Operation Planning

IN all phases of Production Engineering the planning of operations is an essential part of the programme, not only for the immediate production of the component concerned, but to get some idea of machine loading. Since there are many ways in which a workpiece may be made, and the method of manufacture will vary with individual firms and the machines available in the shop, it is a good thing to plan the sequence giving alternatives to each of the individual operations so that if the first selection is not available some other alternative is provided. At this stage we cannot consider the question of machine loading: our main point is the sequence of the manufacturing operations; but the alternative method, if given alongside the ideal method for producing a given article, will go far towards easing the problems sometimes encountered when a preponderance for some type of machine is called for by the operation charts.

Obviously, the main point is to plan the operations and choose the machines so that the piece is produced by the most economical means available. This will decide the tooling required for making the piece, and sometimes it may be necessary to compromise and use or adapt existing tools, toolholders, fixtures, collets, and chuck jaws, etc., rather than specify new material. However, these are points which will be decided when the job in question is considered, and we shall now give our attention to an actual case.

The part shown in Fig. 1 is to be produced, and the first consideration is the quantity involved If this is considerable, it may be worth-while setting up an automatic lathe if one is available; but if the quantity is not large enough or is required only in small batches, then the choice falls on a capstan lathe, and this will be fitted with collets suitable for holding the hexagonal bar from which the job will be made.

Usually an operation chart is used, and these vary in many ways depending on the method used by the operating company. Some include a dimensioned sketch of the workpiece or component, others do not, but merely give the list of operations and machines required for the completion of the work, and a separate detail drawing of the component is issued along with it.

$2\frac{1}{8}$"
$\frac{3}{4}$"
$\frac{1}{8}$"
$\frac{1}{4}$
$\frac{1}{8}$
$\frac{7}{8}$"
$\frac{1}{8}$"
$\frac{1}{16}$"
$\frac{1}{16}$"
60°
60°
$\frac{9}{16}$" B S.F
$\frac{3}{4}$ B S F.
45°
FEED TO STOP
TURRET POSITION NO 1
FACE & CENTRE
TURRET POSITION NO 2
DRILL
TURRET POSITION NO 3.
REAM
TURRET POSITION NO 4
CHAMFER END AT 45 DEGREES
FRONT CROSS SLIDE POSITION NO 4
TURRET POSITION NO 5
CHAMFER AT 60 DEGREES
TURRET POSITION NO 6
CUT THREAD WITH DIE HEAD (SPEED REDUCED)
ROUGH TURN TWO DIAMETERS FRONT CROSS SLIDE POSITION 1.
FINISH TURN 2 DIAS FRONT CROSS SLIDE POSITION 2
UNDERCUT FRONT CROSS SLIDE POSITION NO 3.
PART OFF USING INVERTED TOOL IN REAR CROSS SLIDE.

FIG 1

FIG. 2

The list of operations for making the screwed union shown in Fig. 1 is as follows:

1.	Feed bar to stop . . .	Turret position 1.
2.	Centre and face end . . .	Turret position 2.
3.	Drill	Turret position 3.
4.	Ream	Turret position 4.
5.	Rough turn outside diameters (2)	First position front cross slide.
6.	Finish turn outside diameters .	Second position front cross slide.
7.	Undercut on outside diameters .	Third position front cross slide.
8.	Chamfer $\frac{1}{16}$ in. at 45° . . .	Fourth position front cross slide.
9.	Chamfer bore 60° . . .	Turret position 5.
10.	Cut $\frac{9}{16}$-in. B.S.F. thread . .	Diehead turret position 6.
11.	Part off	Rear cross slide inverted tool.

To complete the piece the $\frac{3}{4}$-in. B.S.F. thread must be cut, and this will need a screwed collet or split screwed bush to hold the $\frac{9}{16}$-in. thread. This operation can be performed on a second capstan, or the first machine setting can be broken down and reset for the remaining operation when all the components have been machined as far as operation 11.

An important point to remember is that the spindle speed must be reduced before the diehead is used to cut the threads. Also the diehead must be self-opening, so that it can be withdrawn after it has cut

FIG. 3—TOOL LAYOUT FOR SCREWED UNION, FIG. 1

OPERATION LAYOUT

PART NUMBER

1m 7/00 (15)

Name of Part	Name of Machine	Date of Issue	Ref

Description of R Material	Amount of R Mat to be issued	Rough Weight	Grade of Material	Manfg Quantity

Oper No	Room No	Description of Operation	Machine Used	Machine Symbol	Time allowed				Quantity	Grade of Operation	Grade of Machine	Jig No	Tools and Gauges	Tray
					Setting up		Operating							
					H	M	H	M						

FIG. 3A

Remarks: Date: Modifications:	Planning Department Operation Layout Sheet:	Part No.

No. of Sheets Sheet No. 1	Name of Part	Division: Spec.:

Prepared.	Checked:	Mat. Spec.:	Mat. Size and Type Assembly
Approved:		Date	

Op. No.	Op. Sym.	Description	Machine	M/C No	Jigs	Tools	Gauges

Firm:

Operation and Tool Layout:	Part No.

Description:	Material.	Date:

Op. No.	Operation	M/C	Dept.	Time		Price	Fixtures	Modifications
				Hrs.	Min.			

TYPICAL OPERATION LAYOUT SHEETS

Fig. 3B

the thread. If a solid die or diehead is used, then the direction of rotation of the machine spindle must be reversed in order to remove the die.

To enable the student to obtain a better idea of the tool layout, this will be given in detail for the following components, after which it should be possible to make out a planning chart or list without the necessity of showing so much detail unless this is specially called for.

The arrangement of the tooling on the turret and front cross slide is shown in Fig. 2. Not all the individual operations are shown, as for example the rough and finish turn of the two diameters, numbers 5 and 6. The same sketch will suffice for both of these, as the cross slide is shown with the requisite tools for the operations required at this stage of the work.

A typical operation chart is shown in Fig. 3A, and this is self-explanatory

FIG. 4—COUPLING PIECE

Another similar component is shown in Fig. 4, and the list of operations for making this is as follows:

Operation No.	*Description*	
1.	Feed bar to stop .	Turret position 1.
2.	Face to length . .	Front cross slide 1.
3.	Rough turn diameter .	Turret-box tool 2.
4.	Finish turn diameter .	Turret-box tool 3.
5.	Form . . .	Front cross slide 2.
6.	Centre drill . .	Turret position 4.
7.	Drill . . .	Turret position 5.
8.	Counterbore . .	Turret position 6.
9.	Part off . . .	Front cross slide 3.

In some cases operations 1 and 6 can be performed together by a combined bar stop and centre, and in some instances facing can also be done at the same time by a combined face and centre tool. A double roller box can be used which carries two sets of tools and rollers, so that roughing and finishing can be done, and also two diameters turned, by the one box tool. By these methods two or three of the operations can be eliminated.

The operations could well be then as follows :

1. Feed to stop and centre.
2. Face to length.
3. Rough and finish turn.
4. Form.
5. Drill.
6. Counterbore.
7. Part off.

The layout of the hexagon turret tools and front cross slide tools are shown in Fig. 5.

Individual operations as performed on turret and capstan lathes are shown in Chapter III, in which the combined bar stop and centre is shown.

In many operation sheets the time for the making of the piece part is given. For a new part this will be an estimated time, the actual time being added when the job has finally been made in the machine shop. To assist in the computation of machining times. the main operations, such as drilling, tapping, turning, milling, planing, etc., will be considered.

Turning

When a bar or similar piece is being turned in a lathe the vital factors are :

1. Cutting speed.
2. Feed.
3. Depth of cut.

The first is dependent on the material, and for our immediate consideration we shall take steel and aluminium. In this connection the cutting speed may vary in so far as carbide-tipped tools with negative rake may be used, and in actual practice the figures employed may be greater than those used in the following examples, which are good average figures suitable for use in calculating cutting times, and are dealt with in detail in Chapter II.

The student will find it good practice to make up suitable tables for himself, and where possible to plot graphs of the various factors, so that it will be possible to use both table and graph to obtain a ready and easy reference.

DRILL
COUNTERBORE
BAR STOP
CENTRE DRILL.
WORK
OP 1. FEED TO STOP.
BOX TURNING TOOL(ROUGH)
BOX TOOL (FINISH)
FACE
FRONT CROSS SLIDE
FORM TOOL
HEXAGON TURRET
PARTING TOOL.
OP 6 CENTRE.
OP. 2. FACE.
OP. 7. DRILL
OP. 3.
TURN
OP. 8. COUNTERBORE.
OP. 4
TURN.
OP. 9. PART-OFF
OP. 5. FORM.

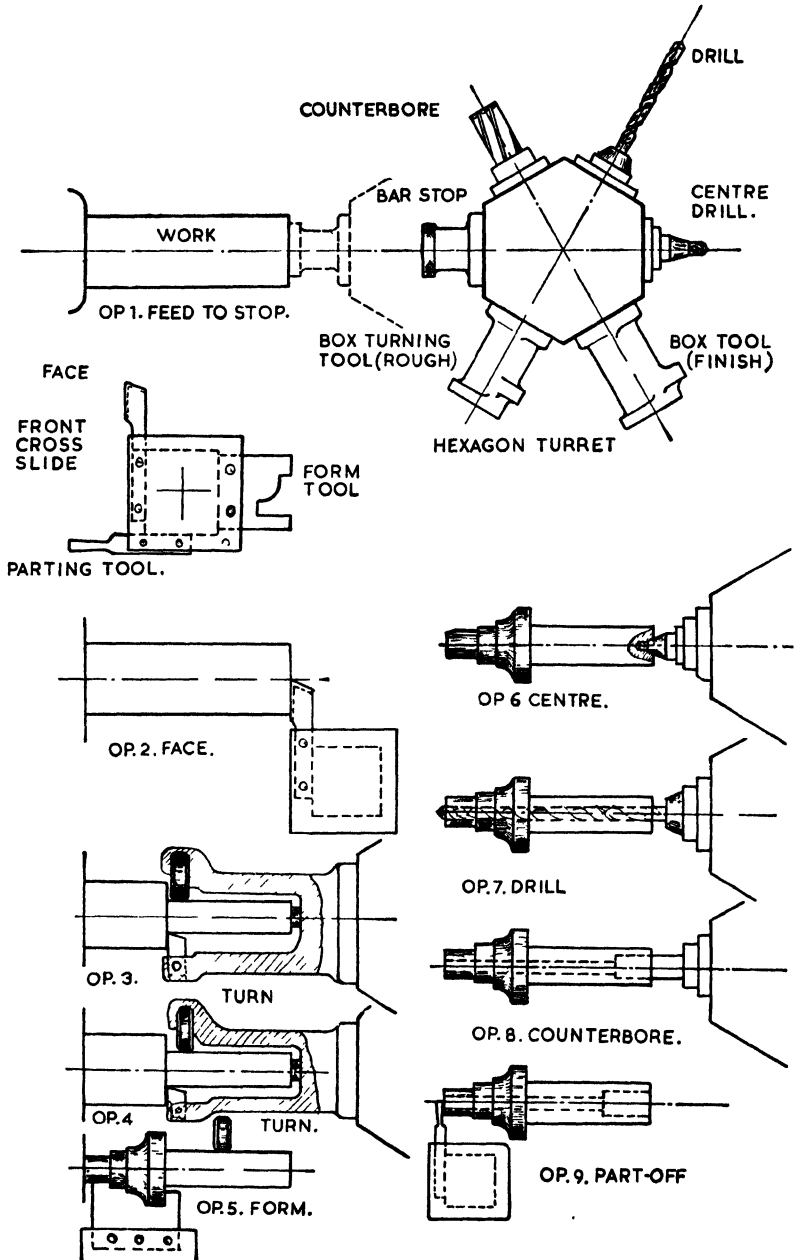



FIG. 5

TABLE 1

Area of Cut Depth × Feed	*Cutting Speed S in Feet per Minute*			
	Mild Steel	*Tough Steel*	*50-ton Steel*	*Cast Iron*
0·001 in.² . .	140	110	80–85	65
0·002 in.² . .	120	85	65–70	55–60
0·004 in.² . .	100	65	50	55
0·008 in.² . .	80	55	40	50
0·016 in.² . .	65	45	35	40

From the data in this table it will be easy to obtain the cutting time for turning operations, and to these must be added handling times—allowances for fatigue, tool grinding, etc., giving what is known as the floor to floor time for a given component.

The various allowances for fatigue, tool grinding, etc., are also given in later tables, and these vary with the operating firm and the system used. The actual cutting time, however, can be calculated as follows :

Suppose the actual cutting time is required for the following turning operation on the shaft shown in Fig. 6.

This can be made by turning down from 3-in. diameter bar, or it could be made from a forging which would only be slightly oversize and could be more easily turned up to the finish sizes. If a large quantity were required, a forging would obviously be used, which we will assume is supplied $\frac{1}{8}$ in. up on finished sizes, leaving $\frac{1}{16}$ in. depth of cut to be removed.

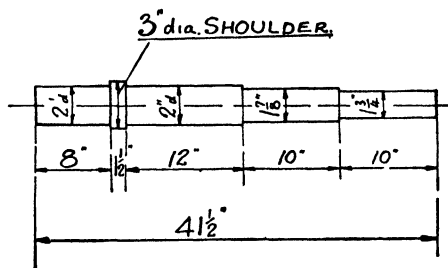



FIG. 6

$$\text{Now } 12S = \pi DN$$

$$\therefore N = \frac{12S}{\pi D}$$

$$= \frac{12 \times 65}{\pi \times 2}$$

$$N = \mathbf{124\ r.p.m.}$$

i.e. revolutions per minute of lathe spindle = 124.

At this stage it should be remembered that the lathe may not have a spindle speed of exactly 124 revolutions per minute available, and there-

fore the nearest speed to this calculated figure must be taken and the times worked out from this. It may of course be near enough to make little or no difference to the actual cutting speed taken from Table 1 and which for this example is taken as 65 ft. per minute:

$$\text{i.e. from table, } S = 65 \text{ ft./min.}$$

Now suppose that the nearest speed available is 130 r.p.m., this will make the cutting speed S equal to 68·1 ft./min., since:

$$12S = \pi DN$$

$$S = \frac{\pi \times 2 \times 130}{12}$$

$$S = 68{\cdot}1 \text{ ft./min.}$$

This can be regarded as near enough for the purpose in hand, and the theoretical cutting time worked out accordingly, using this value of S.

It may be that in some cases two speeds seem equally near to the calculated spindle speed, say one above and one below. In such cases the value of the cutting speed must be found corresponding to each of the two speeds, and then the nearest one decided on for use in the calculations.

Further, it will be noticed that the varying diameters of the bar will also call for varying speeds, and the student should verify for himself that for the $1\frac{7}{8}$-in. diameter portion of the piece the r.p.m. is 132·2 and for the $1\frac{3}{4}$-in. diameter r.p.m. is 141·8, say 132 and 142 r.p.m. respectively.

The rate of feed must now be decided, and this can be taken initially from the area of cut, which obviously is the product of depth of cut and feed.

$$\text{Area of cut} = \text{depth} \times \text{feed} = d \times f.$$

From the table it will be evident that the maximum allowable feed will be 0·064 in., which gives $\frac{1}{0{\cdot}064} = 15{\cdot}63$ cuts per inch, or say 16 cuts per inch, that is, a feed of $\frac{1}{16}$ in. or 0·0625 as against 0·064, a difference of $0{\cdot}064 - 0{\cdot}0625 = 0{\cdot}0015$.

However, this is rather a coarse feed for this particular job and would not be used unless it is to be followed by a finer feed for finishing. In the case under consideration, one cut only is to be taken. Therefore it will be decided that a feed of 48 cuts per inch, or $\frac{1}{48}$-in. feed, will be suitable and the cutting times computed on this basis.

The feed rates provided by various machines vary considerably, and these are dealt with in Chapter VI; the point here is the calculation of cutting times.

Cutting Time

In the following expressions used for the determination of cutting time, either unit length may be considered or the actual length in question,

and unless one is concerned solely with the calculation of cutting times and estimates, it will be better to take the actual length being turned. Incidentally, the cutting tool travels a length greater than the length of bar to be turned, and this must be allowed for. Also, trial cuts have to be taken, and these can be covered by making the length to be cut an increased amount, depending on the conditions prevailing.

For general work allow *a quarter to half an inch* for tool approach and *half to one inch* for trial cuts

$$\text{Time to turn a length } L = \frac{L \text{ in inches} \times \text{Feed in cuts per inch}}{\text{Spindle r.p.m.}}$$

We can here insert the values for the various portions of the bar in the example.

(*a*) Time for 10-in. length $1\frac{7}{8}$ in. diameter
$$= \frac{L \times F}{\text{r.p.m.}} = \frac{(10 + \frac{1}{2} + 1) \times 48}{132} = \frac{11{\cdot}5 \times 48}{132} = \frac{552}{132} = \mathbf{4{\cdot}181 \text{ min.}}$$

(*b*) Time for 10-in. length $1\frac{3}{4}$ in. diameter
$$= \frac{11\frac{1}{2} \times 48}{142} = \frac{552}{142} = \mathbf{3{\cdot}887 \text{ min.}}$$

(*c*) Time for 2-in. diameter 12 + 8 in.
$$= \frac{22 \times 48}{124} = \frac{1056}{124} = \mathbf{8{\cdot}517 \text{ min.}}$$

(*d*) Time for 3-in. diameter shoulder
$$= \frac{2 \times 48}{83} = \frac{96}{83} = \mathbf{1{\cdot}157 \text{ min.}} = \mathbf{1 \text{ min. } 13 \text{ sec.}}$$

The total time for cutting worked out on the theoretical figures is the sum of the individual times found in (*a*), (*b*), (*c*), and (*d*).

Thus, total cutting time $T =$ **17·742 min.**

The time for chucking, centring, turning the bar round, fixing steadies where required, etc., will be allowed for later.

Now, as previously mentioned, the individual speeds which have been found for the various diameters may not be available, and moreover the difference between $1\frac{3}{4}$ in. diameter, $1\frac{7}{8}$ in. diameter and 2 in. diameter is small, and one speed of lathe spindle may, in all probability, suffice for the turning of the shaft, including the 3-in. diameter collar. Assuming

the nearest suitable speed available on the lathe to be **130** r.p.m., the bar can be treated as one length machined at one speed plus, of course, the necessary allowances for approach and trial cuts.

With these assumptions the time for turning the bar will be :

$$T = \frac{L \times 48}{130}$$

$$= \frac{46 \times 48}{130} = \frac{2208}{130}$$

$$T = \mathbf{16{\cdot}98 = 17\ min.}$$

The times just found, viz. 17·7 min. and 17 min., are the times worked out for the actual cutting. To arrive at a figure to be allowed for the job when it is sent into the shops for making, these times must be supplemented by several allowances as follows.

Allowances

A list of the points to be considered will contain the following :

1. Initial check up of piece—may require straightening.
2. Setting in machine—lifting tackle required for heavy work ; also steadies may be needed for long slender or non-rigid pieces.
3. Setting of tools.
4. Trial cuts. Allow 1 in. extra to length to be turned.
5. Tool changing.
6. Speed and feed changes.
7. Actual cutting.
8. Turning workpiece round and rechucking.
9. Special considerations when dealing with unusual or complex parts.
10. Fatigue allowances.

The items listed above may be combined in some instances ; for example, tool changing may be covered by fatigue allowances as will be seen later. In other cases individual consideration will have to be given to the various items, particularly tool resharpening, which will depend on the type of tool used, material, etc., and proximity or otherwise of grinding equipment.

Furthermore, for production work some of the items would not require consideration, parts which required straightening or having excess material would be the subject of supplementary or preliminary operations and would be dealt with separately. This applies particularly to machines which are set up for dealing with work which must be between certain limits, any deviation from which would require special consideration.

It is obvious that each job must be studied and the various points dealt with on their merits. For general considerations, however, we have the following

Chucking

The holding of the work in the machine first receives consideration, and usually falls into two classes: (*a*) held in chuck jaws, (*b*) held between centres.

In (*b*) the work is located on centres, one at the faceplate, from which the work is rotated by means of a driving dog or peg and work carrier, and one at the tailstock. For light work which can easily be manipulated by one hand, 30–35 sec. can be allowed. For parts up to and including 60 lb. weight, where the operator uses both hands, 60 sec. are allowed. If the work is held on a mandrel, the foregoing allowances are increased by 20 sec. for light work, 40 sec. for medium work, and 60 sec. for other parts.

Thus, for a part weighing say 2 lb. weight held between centres, 35 sec. would be allowed, and for the same part held on a mandrel the allowance would be 35 + 20, giving a total of 55 sec.

In (*a*) the type of chuck used will affect the time taken for placing the work in the machine, self-centring jaws being easier to manipulate than independent jaws. The allowances for chucking are as follows:

TABLE 2

CHUCKING TIME IN SECONDS

No.	Method of Holding	Weight of Component, lb.			
		Up to 2	7–10	10–20	30–60
1	Self-centre jaws—work say rough castings	30	60	120	180
2	Special jaws holding on machined surface	20	45	90	120
3	Independent jaws, as in 1	60	120	200	300
4	Hold in special jaws on machined surface and set face true to ± 0·001 in. up to 10 in. diameter	75	150	250	350
5	As in 4 above, but set face and diameter true to ± 0·001 in.	150	350	575	900

Fatigue Allowances

The individual items so far considered are based on the skill and aptitude of the operator, but one cannot continue to perform any function at the same high rate for long periods. An operation that is performed in say 20 sec. at the beginning of the working day will take longer at the end of the day. To allow for this condition a fatigue allowance is made,

and this usually varies between 7½–25 per cent. of the floor to floor time for the component or particular operation. The floor to floor time, usually denoted by F.F.T., is the time taken between picking a workpiece up from the floor or workbin, placing in machine, machining, and then returning to floor or workbin. That is, when a time for machining a piece has been arrived at, including all handling times, chucking times, etc., the figure is increased to allow for the fatigue which is, as stated above, taken as 7½–25 per cent. of the floor to floor time. In the example of the bar the floor to floor time will be 17·7 min. plus chucking time—handling time, fixing steadies, re-chucking, and tool grinding. When this figure is obtained, the fatigue allowance of so much per cent. of this time can be allowed.

A good average figure for fatigue allowance is 12½ per cent. of floor to floor time, applying equally to general turning and drilling operations.

In some turning operations which are of long duration the turner can rest between successive cuts, and where such is the case a smaller allowance can be given. Thus, where the period between cuts is greater than 2 min. (and the turner can rest and has no other duty whilst the cut is proceeding), the allowance for fatigue can be taken at 7½ per cent. If the interval is 2 min. or less, the figure becomes 10 per cent.

In this, as in other instances, no fixed rule can be given which will embrace all conditions, but in general the figures just given will cover the common cases.

	Per cent.
For periods between cuts greater than 2 min., fatigue allowance	= 7½
For periods between cuts less than 2 min., fatigue allowance .	= 10
For general turning	= 12½
Special cases with many unknowns and variables . . .	= 25
For small capstan work	= 15

In some instances the fatigue allowance figure can be increased to allow for points generally considered under separate headings. Thus, in single point turning, i.e. turning with only one cutting tool in operation, a figure of 15 per cent. of floor to floor time can be allowed which will cover fatigue, minor adjustments, and tool setting. Of course, where tools are complicated or are in a multiple set up, it is obvious that they will require more attention, and the allowances for tool grinding and setting will have to be more carefully considered.

Again, to find the time required to produce a workpiece in the workshop will require a knowledge of the time required to set up the machine on which the job is to be done. Some machines are set up by " setters," others by the operator of the machine, known as a " setter operator," and these items really belong to the study of estimating and rate fixing which we are not concerned with here. Our investigation lies in the field of finding the machining time, for we are concerned with the actual

machining operations and the work of the machines when running and not the idle time, although the idle time of a machine is a factor which has to be very carefully considered and means employed for reducing it to a minimum. Figures for setting up machines for general work should be available, if required, to add to the figures decided upon for the actual cutting operations which the production engineer should arrange to be as economical as possible by a judicious arrangement of speeds and feeds commensurate with the plant available.

As a point of interest, it may be noted here that for lathe work a figure of 30 min. can be allowed for preparation, i.e. obtaining drawings, material, tools, setting up, booking job, and similar points. This figure is usually 20 min. for light work on small lathes and 35–40 min. for heavy lathes. These values may have to be modified on old machines in which screw cutting would necessitate change wheels, an extra allowance being made to cover these points. Modern machines, however, have a range of gears in the headstock which will cover a good range of screw threads in much the same way as various feeds are obtained. Turret and capstan lathes are usually set up by special operators, but for a general guide it can be taken that the setting time for these can be obtained from a basic figure of 20 min. or 25 min., plus 5 min. times the number of tools required. Thus, for a small turret or capstan lathe handling say bar $1\frac{1}{2}$–$1\frac{3}{4}$ in. to 2 in. diameter maximum, the setting time could be fixed at $20 + (5 \times 6) = 20 + 30 = 50$ min. if 6 tools were required for a job, and 40 min. if only 4 tools were required.

The foregoing points have been dealt with merely as an illustration of the factors involved in obtaining the total time required for any particular job, needed in cases of quoting a client a price for executing any particular piece of work. The figures given will serve as a guide in the absence of any other fixed or established data.

Returning now to our example, we can complete the study by referring to Table 2 and obtain the chucking time. However, since the weight of the bar is not given, it must be estimated, and this can easily be done by finding the volume of the material in the rough bar or forging and then multiplying by 490 lb. per cubic foot or 0·28 lb. per cubic inch, depending on whether the volume is in cubic feet or inches. Hence, since the volume of the piece in this instance is roughly 142 cub. in., say 145 in.^{3}, the approximate weight will be some 40 lb. and the chucking time allowance will be 180 sec. or 3 min.

Now the piece will have to be centred at both ends before machining can begin—if a centring machine is available, this may take only 2 min., but if it has to be done by marking, centre punch and fitting drill chuck in the lathe tailstock, 10 min. would be needed. Also the ends would require facing, and one end facing to length. Allowing 10 min. for arranging steadies—manipulating them into correct positions for turning —we have the following analysis ·

	Min.	*Min.*
Centre ends	*2*	*10*
Load in chuck and on centre	*3*	*3*
Face ends	4	4
Turn long end	13·747	13·747
Apply steadies and move to position . . .	10	10
Remove bar and rechuck	4	4
Turn short end	4·2	4·2
Turn collar	1·2	1·2
Tool setting (4 times)	4	4
Total time	46·147	54·147
12½ per cent. fatigue allowance	5·8	6·7
	51·947	60·847
Initial preparation, say half-hour . . .	30·0	30·0
	81·947	90·847

The time, then, for the job would be 82 min., using the centring machine, and 91 min. if the bar were centred by marking off and drilling as previously explained.

It should be noted that allowances can be given in the form of additions to the length of the workpiece where this method can be suitably applied, i.e. instead of the 10-in. and 12-in. lengths they could be considered as say 12 or 13 in. and 15 in. long, and the times worked out for these lengths.

The figures used in the above example and those in the tables may be different from those used by individual firms, but they are suitable for the purpose of estimating, and will serve as a basis where no other values are available.

Thus far we have dealt with a turning operation ; but the production of a workpiece may involve drilling, tapping, milling, screwing, and shaping, and in some cases broaching. These individual operations in turn are composed of motions, such as raising and lowering drill spindle, changing drills, taps or reamers, setting workpiece in the fixture or jig, and unloading when machined. These movements are usually termed constituents, and so the production of a finished part from the raw material is carried out by making it undergo a series of processes, each process being made up of operations, each operation being the sum of its constituents, and each constituent in turn being analysed into simple or individual motions.

Some of the processes involve hardening, which depends on the type of material, some of which requires the addition of carbon by a carburising process before it can be hardened. Here, although the component may be machined singly prior to carburising and hardening and ground singly after hardening, it will be packed in a carburising pot with many others,

but by taking the number of pieces placed in the pot, the amount of carburising compound used per pot, the time it is in the furnace, the loading and unloading time, a value for this operation can be obtained. Similarly, the time for normalising, refining, and tempering can all be found, and then from these the time for heat treatment of an individual piece obtained. Such articles as small cylindrical components, ring gears, ball races, collars, etc., are made on automatics, either single-spindle or multi-spindle machines, as individual components. The last operation in the green stage is marking, performed whilst work is still soft. If now we assume that the work is 2 in. diameter, 1 in. deep, and $\frac{1}{4}$ in. thick, and is to be given a case depth of some fifty to sixty thousandths of an inch (0·050–0·060), the carburising pot of reasonable size for this work will hold say 100 components.

The pot, compound, and components will have to reach the furnace temperature by " soaking," and this will take say 4–5 hours. Then the penetration of carbon commences, and the rate of penetration depends on the temperature, which is usually 900–920° C. At this temperature the work would require a further 5 or 6 hours, giving say 10 hours' furnace time. Thus each component for the carburising operation will require $\frac{10}{100}$ hours $= \frac{600}{100} = 6$ min., and this figure can be included in the times on the operation layout where such heat treatment is called for.

Similarly, all heat-treatment operations—normalising, refining, and tempering—can be dealt with.

Drilling

Under this heading we will deal with reaming and tapping operations as well as drilling, and in dealing with these points altogether the object is to consider each particular operation so that when a component is to be made or machined, all the operations involved can be visualised and the actual cutting time for each individual operation appreciated. In many cases the various operations called for are performed on separate machines, such as turning, drilling, milling, etc., and this method would undoubtedly apply where small quantities of the product are being dealt with. On the other hand, a large enough quantity of the workpiece would quite easily warrant the setting up of an automatic machine to produce the parts, and in such a case all the operations required would be dealt with on the one machine.

Since the individual machines are still used extensively for the operation for which they were designed, a study of their cutting or operation times is necessary.

As with the other operations, so with drilling, the quantity will affect the time required to produce the finished part. Small quantities will probably be marked out, centre holes made by a centre punch and, for small work, manipulated entirely by hand. The same piece in quantities sufficiently large to warrant a jig would be held and located in a jig whilst

the drilling proceeds. Again, the quantity of parts will decide whether a multi-spindle drill will be warranted or a single-spindle drill used to drill the holes required in the workpiece.

These various points, however, do not enter into the initial consideration, which concerns the actual time the drill takes to penetrate a given workpiece, and to obtain the drilling time for a component the method employed follows that for turning. First, the cutting speed must be determined, and from this and the drill diameter the number of revolutions of the drill spindle can be obtained. For example, if we assume that a hole ½ in. diameter is to be drilled in a mild-steel plate at a cutting speed of 90 ft. per min., obviously the drill must make 687·3 r.p.m., since:

$$N = \frac{12S}{\pi D}$$

$$= \frac{12 \times 90}{\pi \times \frac{1}{2}}$$

$$= \frac{2160}{\pi}$$

$$\therefore N = \mathbf{687{\cdot}3\ r.p.m.}$$

In like manner all spindle r.p.m. can be obtained for any given operating conditions.

The feed must now be considered, and this is usually given in inches per revolution. For purposes of illustration, suppose a drill is making 1,000 r.p.m. and has a feed rate of 0·005 in. per revolution

$$\text{Then feed in in. per minute} = 1000 \times 0{\cdot}005$$
$$\text{Feed} = \mathbf{5\ in./min.}$$

Similarly, to drill a hole 1 in. deep at the above rate will take $\frac{1}{5}$ min.

$$= \frac{60}{5} = \mathbf{12\ sec.}$$

Tables giving figures for drilling a 1-in. length can be built up by finding the time to drill this length, say for mild steel, at 90 ft. per minute for drill diameters from $\frac{1}{16}$ in. up to 1½ in. in the standard drill sizes. This table would include ·

(*a*) Drill diameter.
(*b*) Spindle r.p.m.
(*c*) Feed per revolution.
(*d*) Feed per minute.
(*e*) Time to drill 1-in. length.

If necessary, or found desirable, the number of revolutions made by spindle during the drilling of the 1-in. length could also be included. With such a set of figures the estimation of the drilling time can quite

easily be performed, as obviously from the foregoing the time needed to drill a ½-in. diameter hole 1½ in. deep in mild steel at a cutting speed of 90 ft. per minute will be 1½ × 12 or 18 sec.

This method can be extended to cover various cutting speeds, and the range of drill sizes extended to say 2 in. diameter or reduced to 1 in. or 1¼ in., or any suitable range which might be called for in any particular phase of drilling.

As in all other cases, no hard and fast or inflexible rules can be given, since conditions will vary with the size, type, and make of drill, and possibly the spindle speeds available may not readily conform to the calculated figures. As a general guide, however, the following figures will be found reasonably accurate for normal purposes, and the tables can be used for obtaining cutting speeds and feeds.

Drills for general use are made from high-speed steel and carbon steel. and as a general rule the speeds for high-speed steel drills are twice those for drills made from carbon steel.

TABLE 3

CUTTING SPEEDS IN FT. PER MINUTE

Material	*Cutting Speed*	
	H.S.S. Drills	*Carbon Steel Drills*
Mild steel, cast iron .	80–100	40–50
Hard tool steels, alloy steels . . .	40–60	30–35
Bronze, brass, and non-ferrous metals . .	200	85–90
Bakelite, aluminium, vulcanite, etc. . .	350–400	150–180

It should be remembered that a suitable lubricant or cutting compound will in many instances increase the cutting speed over the figure obtainable when no coolant or lubricant is used.

Feeds

For drills up to ¼ in. diameter 0·001–0·005 in. per revolution
½ in. diameter 0·006–0·010 in. per revolution
1 in. diameter 0·0105–0·014 in. per revolution
1½ in. diameter 0·014–0·016 in. per revolution
2 in. diameter 0·017 in. per revolution

The above table gives a good general guide, but for more detail the following table extends this information.

TABLE 4

FEED PER REVOLUTION OF DRILL

Drill Diameter, in.	1/32	1/16	3/32	1/8	5/32	3/16	7/32	1/4
Feed per revolution, in. . . .	0·001	0·002	0·0025	0·003	0·004	0·005	0·0055	0·006
Drill Diameter, in.	9/32	5/16	11/32	3/8	7/16	1/2	9/16	5/8
Feed per revolution, in. . . .	0·0065	0·007	0·0075	0·008	0·009	0·010	0·0105	0·011
Drill Diameter, in.	11/16	3/4	7/8	1	1 1/8	1 1/4	1 1/2	
Feed per revolution, in. . . .	0·0115	0·012	0·013	0·014	0·015	0·016	0·017	

Where the drilling is followed by a reaming operation, the drill is taken out of the drill chuck and a reamer inserted. The cutting speed for the reamer is usually one-half the drill speed, but since the feed is approximately twice that for drilling, the time to ream a hole is the same as that for drilling it immediately prior to reaming.

For tapping, however, the speed must be reduced.

TABLE 5

TAPPING SPEEDS IN FT. PER MINUTE

Material	*Speed*
Cast iron	20–25
Mild steel	15–20
Free cutting steel . . .	25–50
Tough steel	8–10
Brass, copper	60–80
Aluminium . . .	150–160

For tapping a hole after drilling, the spindle r.p.m. can be found as in previous examples, using the above cutting speeds as a guide.

Taking now an example, we will suppose that a component is made in cast iron and has in all ten holes of varying diameters and depths, some of which require tapping and some reaming. We shall first find the

cutting time, and then as a point of interest add on the various allowances in order to find the floor to floor time in a similar manner to that used in the turning example.

Let the ten holes be of the following dimensions:

Two 1-in. diameter holes $1\frac{1}{2}$ in. deep.
Two $\frac{1}{2}$-in. diameter holes $\frac{3}{4}$ in. deep.
One $\frac{3}{8}$-in. diameter holes $\frac{3}{4}$ in. deep, reamed.
Two $\frac{5}{16}$-in. diameter holes $\frac{1}{2}$ in. deep.
Two $\frac{1}{4}$-in. diameter holes $\frac{3}{8}$ in. deep, tapped $\frac{1}{4}$ in. B.S.F.

Referring to the table of cutting speeds, it is found that for high-speed steel drills the figure is between 80–100 ft. per minute, and we shall decide on 90 ft. per minute.

The drill spindle must make the necessary revolutions per minute to give this cutting speed, and the calculations are the same as those used previously. For the 1-in. diameter hole the spindle revolutions will be—

$$N = \frac{12S}{\pi D} = \frac{12 \times 90}{\pi \times 1} = \frac{1080}{\pi}$$

$$N = 343{\cdot}6 \text{ r.p.m.}$$

In a similar manner the other spindle speeds can be obtained, but the student can more readily obtain the necessary values from tables if these are to hand, and the figures for the various diameters are:

$\frac{1}{2}$-in. diameter hole 688 r.p.m.
$\frac{3}{8}$-in. diameter hole 917 r.p.m.
$\frac{5}{16}$-in. diameter hole 1,104 r.p.m.
$\frac{1}{4}$-in. diameter hole 1,376 r.p.m.

It will be seen that not all the holes can be successfully cut on one spindle speed, since there is too great a variation between the extreme speeds of 344 r.p.m. and 1,375 r.p.m. Where the size of the holes is such that the difference in the spindle revolutions is not too great, one speed can be used, or alternatively two speeds could be used—a high speed for the smaller hole sizes and a low speed for the larger holes. This latter method lends itself to say a two-spindle drilling machine, where the two spindles could be made to run one at each of the desired speeds, and the holes could then be dealt with successively by the two spindles.

Returning to the example, we have the following lengths to drill:

1-in. diameter holes $2 \times 1\frac{1}{2} = 3$ in.
$\frac{1}{2}$-in. diameter holes $2 \times \frac{3}{4} = 1\frac{1}{2}$ in.
$\frac{3}{8}$-in. diameter holes $1 \times \frac{3}{4} = \frac{3}{4}$ in. drill and ream.
$\frac{5}{16}$-in. diameter holes $2 \times \frac{1}{2} = 1$ in.
$\frac{1}{4}$-in. diameter holes $2 \times \frac{3}{8} = \frac{3}{4}$ in. drill and tap.

The time for the actual drilling operations will be as follows. First we must determine the rate of feed in the manner already indicated.

For the 1-in. diameter holes the feed is 0·014 in. per revolution of the drill spindle ; clearly, then, the feed rate will be spindle revolutions times feed, and will be equal to ~~344 × 0·014 = 3·9 in.~~ per minute, and it will take therefore 16 sec to drill a depth of 1 in

A glance will show that the time to drill the 1-in. depth will be roughly $\frac{1}{4}$ min. or $\frac{1}{3{\cdot}9}$ more exactly.

From this we can find the time to drill the 3 in. required to produce the two 1-in. diameter holes, which is obviously

The other holes can be treated in a similar manner.

Now when these figures are worked out they will invariably give different values for the feeds and some of them will not be available on the machine, and it so happens that just as the spindle speeds as found by calculation have to be approximated to those available on the drill which is to be used, so the calculated rates of feed must also conform to the feeds available on the drilling machine which is to perform the drilling.

If one feed rate is decided upon, then all that is required is to multiply this by the total length to be drilled, in this particular case $3 + 1\frac{1}{2} + \frac{3}{4} + 1 + \frac{3}{4}$ in., giving a total of 7 in., plus $\frac{3}{4}$ in. for the reaming of the $\frac{3}{8}$-in. diameter hole.

This, then, gives a total of $7\frac{3}{4}$ in. to be drilled at the rate of $\frac{60}{3{\cdot}9} = 15{\cdot}4$ sec., which we have taken to be 16 sec. per inch length.

The time for drilling and reaming will then be given by :

$$16 \times 7\tfrac{3}{4} = \mathbf{124\ sec.}$$

The tapping must now be carried out, and the speed for this from Table 5 is 20 ft. per minute.

The time required for tapping will be given by :

$$T = \frac{L \times 60 \times T.P.I.}{\text{R.P.M.}}$$

For the length of tapped hole the tap must travel an extra amount equal to the lead of tap, usually about half the diameter, and moreover the tap must be removed after it has done its work. The time for the withdrawal of the tap is dependent on the speed of the reverse, and if this is the same as the forward speed, then the time for tapping will be :

$$T = \frac{2 \times (\frac{3}{4} + \frac{3}{8}) \times 60 \times 26}{300}$$

$$T = 11{\cdot}7 \text{ sec.}$$

$$\text{i.e. } T = \mathbf{12\ sec.}$$

Now the total cutting time without any of the allowances is 124 + 12 = 136 sec., and this figure could be used when comparing cutting times or other similar factors. If, however, the time for the workpiece, including

loading into jig, manipulating the jig and drill-spindle lever, changing drills and slip bushes for taps and reamer, then these factors must be added to the 136 sec. just calculated.

Drill changes are made usually in 5 or 6 sec. Drill bushes of the removable or slip-bush type 15–20 sec., and taps 25–30 sec. With these factors included, the time now becomes :

	Sec.
Drill, ream, and tap . . .	136
Load into jig and unload . .	30
Raise and lower drill spindle .	50
Change 5 drills	30
Change reamer and slip bush .	30
Change tap and slip bush . .	50
	326

Fatigue allowance, including tool sharpening, 12½ per cent. :

$$12\tfrac{1}{2} \text{ per cent. of } 326 = \mathbf{41\ sec.}$$

Thus the total time for the piece will be :

$$326 + 41 = 367 \text{ sec.} = \mathbf{6\ min.\ 7\ sec.}$$

In the summary it will be noted that an item of 30 sec. is allowed for loading the work into the jig. In the absence of any established data, the following times can be allowed :

For simple jigs (plate) . .	6 sec.
For open-type jigs . . .	15 sec.
For box-type jigs . . .	25 sec.

These times are averages for handling a light workpiece, say up to and including 2 lb. weight. For pieces up to and including 10 lb. weight multiply the above times by a factor of 1·8–2, and for pieces over 10 lb. weight use a factor of 3.

Of course, special features, such as unduly heavy or difficult pieces to handle, would have to be treated individually and the time for loading carefully considered. The design of the jig should allow for easy loading, quick and secure clamping, and positive location of the work, as these factors play an important part in the reduction of loading time and also on the fatigue of the operator.

The usual type of mass-produced component which calls for a drilling, reaming, and tapping operation can be initially dealt with by the methods outlined in the foregoing example. Where a drilling operation is part of the machining done on a capstan lathe with a drill located in one of the turret faces, the times may be a little different from those obtaining on a standard-type drilling machine. If the feed rates available on the auto-

matic feed are not suitable, the drill will have to be fed in by hand, and the spindle speed will in all probability be limited to that used for other operations on the bar material. However, with these latter points settled the calculation of the drilling time is the same as in the examples already dealt with.

Planing, Shaping, and Slotting Operations

In the case of work being turned up in a lathe the tool is in contact with the work from the beginning, that is, from the start of the cut to the finish, and there is no lost or idle movement. With planing, shaping, and slotting machines, however, and in fact with any machine having a reciprocating motion, there is a waste of time in idle return strokes. Moreover, the type of drive limits the maximum speed, and also gives rise to a variable rate of cutting, since at the beginning of its forward or cutting stroke it has no velocity ; but the velocity increases to a maximum at the centre of stroke and falls away to zero at the end of the cutting stroke. It then reverses direction and travels at a quicker return rate than the cutting rate, the ratio of return stroke to cutting stroke being 2 : 1 approximately.

The rate of cutting is not only variable, but it is not continuous, no work being done on the return stroke. Suppose now that a planing machine table moves forward a distance of 8 ft. five times in 1 min., the product of these two quantities 8 ft. × 5 per minute gives a result of 40 ft. per minute, and this is known as the effective speed. Now in making the 5 forward or cutting strokes the table must also make 5 return strokes in order to be in a position for making a sixth forward stroke. The return being quicker than forward motion as already stated, the time for one complete stroke will be $\frac{1}{5}$ min. or 12 sec. In this 12 sec. the table of the planing machine moves forward 8 ft. at the cutting speed and backward 8 ft. at the return speed. For the purpose of illustration it will be assumed that the ratio of speeds is 2 : 1, giving a cutting time of 8 sec. and return time of 4 sec.

Now the 8-ft. cutting stroke takes 8 sec., that is, the table must be moving 1 ft. each second, giving a cutting speed of 60 ft. per minute which, since the forward motion of the table is made at variable speed, is an average value.

Thus far we have found for this example :

The effective speed = 40 ft./min.
The average cutting speed = 60 ft./ min.
The average return speed = 120 ft./min.

To solve a problem that involves the use of a planing machine it is only necessary to make the necessary allowances to length and breadth of the workpiece in order to obtain the length of stroke required and tool cross travel, and then the cutting time can be found in the usual manner as follows. A surface 6 ft. long by 2 ft. wide is to be planed at the rate

of 60 ft. per minute given above and at a feed of $\frac{1}{8}$ in. which is a feed used for semi-finishing cuts for cast iron where the depth of cut is not greater than $\frac{3}{16}$ in.

Length of stroke 6 ft. + allowance	= 7 ft.
Width of tool travel 2 ft. + allowance	= 2 ft. + 2 in. each side.
Average cutting speed	= 60 ft./min.
Feed per stroke	= $\frac{1}{8}$ in.

To find the cutting time it will be simpler if the time for one complete stroke is found, that is cutting and return, which for 8 ft. is found to be 12 sec. ; thus, for 7-ft. stroke at this rate the time will be :

$$\text{Time per stroke of 7 ft.} = \frac{7 \times 12}{8} = 10\tfrac{1}{2} \text{ sec.}$$

$$\text{In 2 ft. 4 in. there are } 28 \times 8 = 224$$

$$\text{No. of strokes} = 224$$

$$\text{Time to plane } 6 \times 2 \text{ ft.} = 10\tfrac{1}{2} \times 224$$

$$= 2{,}352 \text{ sec.}$$

$$= 39{\cdot}2 \text{ min.}$$

$$\text{Cutting time} = 40 \text{ min.}$$

If a fatigue allowance is to be taken into consideration this can be 15 per cent. of the cutting time, plus the time taken to load the work on to the machine and setting the tools for the work in hand.

Planing machines are often used as a means of mass production in so far that a machine with a long table can accommodate a considerable number of similar components arranged in a series of long rows. Such an example can be seen in planing the slides in the sides of railway axle-boxes, of which a fair number can be machined at one setting. The time taken to load the number on the table plus the total machining time when divided by the number of boxes will give the time for one slide.

Large components such as the one used in the illustration are not produced in great quantity, and can be dealt with as indicated ; but a similar area comprising a number of smaller components is one more likely to be met with. It is true these smaller parts could be machined on a shaper, and reasonably fast cutting speeds are available on the latest type of shaping machines.

Shaping Machines

The remarks for planing machines apply equally well to shaping machines, which are very similar ; the main difference being that in the planer the tool is stationary and the table reciprocates, whereas in the shaper the tool which is carried on the moving ram of the machine reciprocates and the work remains stationary.

The relationship between the effective speed and average cutting speed is similar to that used in planing, a good figure being three-fifths.

$$\textit{Effective cutting speed} = \frac{3}{-} \times \frac{\text{Cutting speed}}{5} \text{ ft./min.}$$

Suppose a shaping machine is operating on a stroke of 18 in. and makes 25 strokes per minute. As in the case of the planer, the effective cutting speed is given by:

Length of stroke in feet × Number of strokes per minute

$$\text{Effective speed } E = L \times N$$

$$\text{Then } E = \tfrac{18}{12} \times 25 = \tfrac{3}{2} \times 25$$

$$= \mathbf{37\tfrac{1}{2}\ ft./min.}$$

The ratio of the cutting stroke to the return stroke is generally between $1\frac{1}{2} : 1$ and $2 : 1$, and if we take the lower value the example can be worked out as for the planing machine.

$$25 \text{ strokes per minute} = \tfrac{60}{25} \text{ sec. per stroke}$$

$$= \mathbf{2{\cdot}4\ sec.\ per\ stroke}$$

For $1\frac{1}{2} : 1$ ratio the 2·4 sec. is divided by $2\frac{1}{2}$, giving 0·96. Thus the time of cutting stroke is $0{\cdot}96 \times 1\frac{1}{2} = 1{\cdot}44$ sec. and the time for the return stroke 0·96 sec., giving 2·4 sec. for one complete stroke.

Thus the cutting speed will average $37\frac{1}{2}$ ft. in 1 min., modified by the 1·44 sec. as follows.

$$\text{Time for 1 ft. stroke} = \frac{60}{37\frac{1}{2}} \text{ sec.}$$

$$\text{Time for } 1\tfrac{1}{2} \text{ ft. } (\tfrac{18}{12}) = \frac{60}{37\frac{1}{2}} \times 1\tfrac{1}{2} = \tfrac{120}{75} \times \tfrac{3}{2}$$

$$= 1{\cdot}6 \times \tfrac{3}{2} = \mathbf{2{\cdot}4\ sec.\ as\ above}$$

From this we see 1 ft. is covered in 1·6 sec., but the actual stroke of $1\frac{1}{2}$ ft. is covered in 1·44 sec.; therefore, the average cutting speed is

$$\frac{37{\cdot}5 \times 1{\cdot}6}{1{\cdot}44} = \frac{60}{1{\cdot}44}$$

Average cutting speed = 41·7, say **42 ft./min.**

Return stroke speed $= \frac{60}{0{\cdot}96} =$ **66·8 ft./min.**, say **67 ft./min.**

When these details are known, the cutting times can be worked out along the lines already indicated. The slotting machine can justifiably be likened to a vertical shaping machine, its action being similar to a shaper, except that the tool travels in a vertical plane, whereas the shaper is in a horizontal plane. For general problems, however, the two machines can be treated as being the same so far as cutting time calculations are concerned.

Broaching

Many operations previously performed on other types of machine tools are now done on broaching machines. In surface broaching, flat surfaces are broached and a good surface finish is obtained. Holes of square, round, and hexagonal shape, keyways, splines, and internal gears are

broached, and modern machines can produce a splined hole in a component *to fine limits in much less time than by any other method.*

The time taken in broaching a part is dependent on the amount of metal to be removed and the physical properties of the workpiece. The metal to be removed will control the length of broach, and this is also limited by the stroke of the broaching machine.

The pitch of broach teeth is dealt with in the work on *Jig and Tool Design*, but it can be stated here that the pitch p is given by:

$$p = 0{\cdot}35\sqrt{\text{length of hole to be broached}}$$

$$p = 0{\cdot}35\sqrt{L}$$

This pitch times the number of broach teeth will give the length of broach, and this will determine the time taken to pull or push the broach through the work.

If a new component is to be broached, an estimate of the time can be arrived at by assuming a " rise per tooth " which, when divided into the amount of metal to be removed, will give the number of teeth. The number of teeth times the pitch will give the cutting length of the broach, and from this an overall length of broach can be assumed by allowing for finishing teeth, pilot, and fixing to the machine, and this total figure can be used to find the broaching time, for it is clearly seen that if a broach is 6 ft. in length and it is to be drawn through a component at a cutting speed of 5 ft. per minute, the time taken will be $\frac{6}{5} = 1\frac{1}{5}$ min., or 72 sec.

With the usual allowances added, this will give the times as worked out for other operations.

For small broaches the rise per tooth for broaching steel parts is 0·001–0·003 in. and for cast iron and brass 0·002–0·006 in.

For larger broaches the rise per tooth can be taken as being between 0·005–0·010 in.

The cutting speeds vary with the material being cut, and values for these cutting speeds will be found in Table 6.

TABLE 6

CUTTING SPEEDS FOR BROACHES IN FT. PER MINUTE

Material	*Cutting Speed*
Steel, soft	30
Steel, medium	20
Steel, hard	10
Brass	40
Bronze	40
Copper	10
Cast iron, soft	40
Cast iron, hard	20

The speeds of operation of broaching machines vary with the type and size of machine, and the usual range lies between 4 ft. per minute and 40 ft. per minute. The return speeds, which are faster, may be up to 150 ft. per minute and as low as 10 or 15 ft. per minute, an average figure being 40–45 ft. per minute for lower cutting speeds and 80–120 ft. per minute for the higher cutting speeds, the ratio of return to cutting speeds being approximately 2 : 1.

Milling

In the operations so far considered the size of the cutting tool has not influenced the tool travel required to complete a cut, but in milling opera-

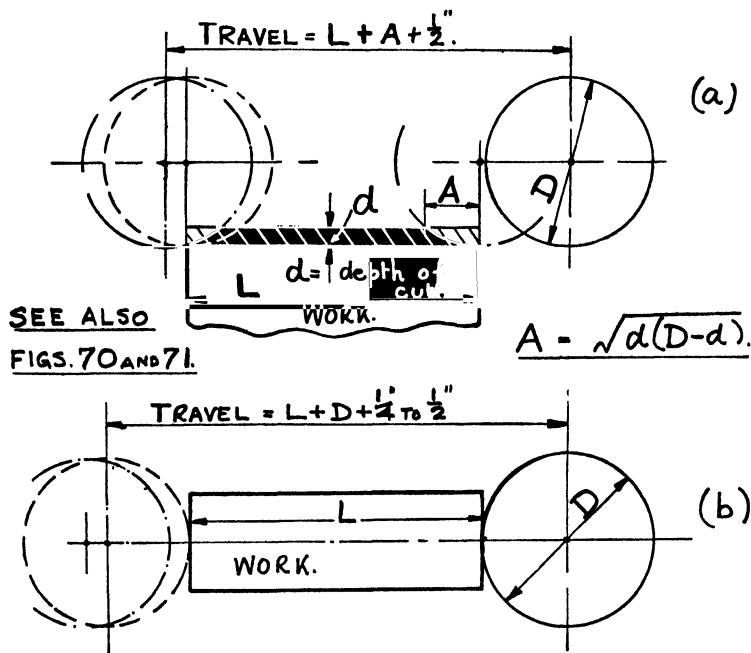



FIG. 7

tions this is not so. Apart from the limitations due to shape or form of cutter, the cutter diameter will determine the amount of travel necessary to complete the passage of the cutter over the workpiece. The approach or "start," as it is sometimes called, is dependent on the cutter diameter, and in order to keep the travel to a minimum the smallest diameter of cutter which it is possible to use for any particular operation should be chosen.

The total travel required per cut consists of:

1. The approach.
2. Length of surface to be milled.
3. Overrun.

These three items are shown in the sketch. Fig. 7 (a) indicates a horizontal machine and Fig. 7 (*b*) shows a vertical machine. See also Figs. 70 and 71.

Where only one cut is required on a workpiece it is obvious that the time required for this one pass will be :

$$T = \frac{\text{Total travel of cut}}{\text{Feed per minute}} \text{ minutes.}$$

Suppose a face milling operation of one cut requires a total travel of 16 in., and the table feed is 4 in. per minute, then from the above it can clearly be seen that the time will be 4 min., or 240 sec. if the time is preferred in the latter unit.

Since the cuts are usually heavy, a suitable fixture or machine vice must be employed to hold the work, and the time allowed for loading the work into the fixture for the machining operation and removing it after the operation has been completed.

The times for loading can be taken as the same as those for loading drill jigs of the open type, which will give the following figures for the loading time in seconds.

TABLE 7

Weight :	*Up to* 2 *lb.*	2–10 *lb.*	*Over* 10 *lb.*
Time in seconds . .	15	30	45

The items for ascertaining the time for a given milling operation can be listed thus :

1. Load.
2. Approach.
3. Mill surface and overtravel to clear the cut.
4. Travel back to start position.
5. Unload.
6. Gauge.

In cases where more than one cut is taken, as in a rough and finish cut, there will be the additional time involved for setting the cutters to the correct cutting depths.

1. Load.
2. Adjust height (cutter or table) for first cut (rough).
3. Approach.
4. Mill surface and overtravel to clear.
5. Return to start.
6. Adjust height for second cut (finish).
7. Mill surface and overtravel to clear.
8. Return to start.
9. Unload.
10. Gauge.

Of course, the first cut can be extended so that the cutter travels well clear of the work and is then in such a position that it can be returned to the start and reset for the second cut. The setting of the milling cutters in the first instance is important and this can be done by machine adjustment using the graduated dials on the machine or by a setting block in cases where the work is held in a milling fixture provided with a setting block, see Vol. II, *Jig and Tool Design*, pp. 75–78, where information on this subject of setting blocks and gauges is dealt with.

Rotary or continuous milling, in which the work is held in fixtures which are fixed to a revolving table, is suitable for certain components. When a finished part is taken out of one of the fixtures a rough one is put in its place and the table revolves continuously. In some special machines two spindles are provided, and in this way components such as connecting rods for internal-combustion engines can have both ends machined at once, and this fact, coupled with the rotary table, gives a high production rate.

The time for one component by this method, as can readily be seen, is given by:

$$T = \frac{\text{Time for one revolution of table}}{\text{Number of components per revolution}}$$

For a revolving table making one revolution in 2 min. and holding 6 components, the time per component will be:

$$T = \frac{2 \times 60}{6}$$

$$\text{Time } T = \textbf{20 sec.}$$

The average figure for fatigue allowance on this class of milling is 15 per cent.

For components such as castings, etc., which may have hard spots or present other difficulties, or where a fine finish or accuracy is required, an additional 20 per cent. of the cutting time is added to cover the extra machining which may be necessary on the finishing cuts to obtain the required accuracy.

This 20 per cent. allowance is usually taken as 20 per cent. of the time nominally required for the finishing cut only.

In the ordinary milling operations where the table is returned to the starting position, the time will vary in so far as the operation is performed by normal return feed, quick power traverse, or wound back by hand. The power traverse can be accomplished rapidly and the rate readily obtained from the machine, and is only a few seconds. For winding the table back by hand an average figure is 15–20 sec. per foot of travel.

Grinding

In comparison with other methods of machining, grinding is performed at a much greater speed, i.e. it has a higher cutting speed. With these

high speeds the danger due to wheel breakage is increased, and to allow for this there is a legal limit to grinding speed of 6,000 ft. per minute. This does not mean to say that grinding wheels must revolve at 6,000 r.p.m. irrespective of size, nor that it should always be necessary to revolve the wheel at the rate to obtain 6,000 ft. per minute cutting speed. In fact, speeds for grinding vary normally between 3,000 and 4,500 ft. per minute, and for small-diameter wheels, such as small-bore grinding, the number of revolutions per minute must be of the order of 20,000.

The stock removal is small, that is to say, the amount of material which is to be removed even on large diameters is measured in thousandths of an inch, which is a natural sequence when it is considered that in most cases the workpiece has previously been prepared by turning, milling, boring, or some similar operation, prior to finishing by grinding. The amount of stock which is to be removed is called the grinding allowance, and this is one of the important factors in calculating the time required for a particular grinding operation.

Where a company is operating on the production of many sizes of cylindrical components which may only vary by small amounts from each other, the times for grinding operations are tabulated ; for example, bore grinding for diameters from ½ in. to 6 in. and of varying widths from ¾ to 2½ or 3 in. may be tabulated and the times worked out for varying amounts of stock removal.

The general amount of grinding allowance varies with the diameter of the component and the finish required, i.e. the amount of accuracy and the tendency of the material to warp or distort in hardening. There is some *soft grinding* done, but the great majority is performed after the parts have been hardened, and if in hardening the part distorts, there may be *ovality* in the bore, or lack of concentricity on the outside diameter, and where this is likely to occur, the grinding allowance must provide for this.

Surface Grinding

In surface grinding, the work remains stationary on the table, which has a traverse motion under the grinding wheel and either (*a*) reciprocates or (*b*) revolves as in the " Blanchard " surface grinder ; in each case, the operation is similar to milling operations, (*a*) being similar to ordinary milling practice, and (*b*) similar to rotary or continuous milling.

From the foregoing it is easy to see that the calculation of the time required for a surface grinding operation is but a modification of that for milling operations. On a plain surface grinder the work is usually held on a flat magnetic chuck, some being of the permanent magnet type, others being magnetised when the electric current is switched on. By this means the loading time is very small, being approximately 4 sec. for small flat parts, 6 sec. for components 15–20 sq. in. in area and about 10 sec. for larger work

The cut taken per pass of the wheel over the work is usually of the following order:

Roughing cuts . .	0·003–0·004 in.
General grinding . .	0·002 in.
Commercial grinding .	0·001 in. for standard finish
Fine finishing cut .	0·0005 in.
Fine finish to close limits	0·0001 in., with diamond dressed wheel.

The circular table machine sometimes has work holders or fixtures into which the work is placed whilst the table is revolving, and the process is continuous, a ground component being taken out and a rough one put in its place. The loading times are usually between 2 and 4 sec. Other rotary machines have an automatic feed for the work, which is fed down a chute on to the table to pass under the grinding wheel, and when finished meets a deflector which guides it into the workbin or on to a stand.

The speed of the table is 50–60 ft. per minute where the face to be ground is not a continuous one or of large area, and 30–35 for continuous grinding across the face of the work. For the reciprocating table machine the table speed is usually slower, the corresponding figures being 20–30 ft. per minute for non-continuous surfaces, 10–15 ft. per minute for continuous surfaces. The figures will, of course, vary according to the area and type of cut and stock removal. Moreover, an overrun of the table will be required to ensure the grinding wheel clears the work.

It will be obvious that the actual time required for a grinding operation will be given by the division of the total amount to be removed from the work by the depth removed per minute.

In addition to the actual grinding allowance, there is a compensation allowance made which is of the following order:

For tolerances of 0·002 in. and upwards, allowance	= 0·010 in.
For tolerances 0·001–0·002 in., allowance	= 0·020 in.
For tolerances below 0·001 in., allowance	= 0·040 in.

That is to say, the actual grinding allowance is increased by the above compensation allowances, which vary according to the finish required, being greater for the finer finishes and limits.

$$\text{Grinding time} = \frac{\text{Total allowance (Grinding + Compensation)}}{\text{Feed per minute}}$$

$$\text{Feed per minute} = \text{Feed per pass} \times \text{No. passes per minute.}$$

If a grinding machine table holds 6 pieces of a given workpiece on the magnetic chuck and the parts require 0·025 in. removing from one side, tolerance 0·003 in.; wheel diameter is 12 in. and length over the 6 parts is 18 in. and speed of table traverse is 15 ft. per minute, calculate the approximate floor to floor time.

$$\text{Loading time} = 6 \times 4 = 24 \text{ sec.}$$

$$\text{Grinding time} = \frac{0{\cdot}025 + 0{\cdot}010}{\text{Feed per minute}} \times 60$$

$$= \frac{0{\cdot}035 \times 60}{0{\cdot}012}$$

$$= \mathbf{175 \text{ sec.}}$$

Note.—The number of passes required per minute will be given by dividing the table feed by the length of table travel:

$$\text{No. of passes} = \frac{15 \times 12}{18 + 12} = \frac{15 \times 12}{30}$$

Passes required = 6.
Feed per pass = 0·002 in. (see values given)
∴ Feed per minute = 6 × 0·002
= **0·012**

Allowing a handling time of 60 sec., 40 sec. for gauging the work, and 20 sec. for wheel dressing which is the equivalent to tool grinding, the total time required will be:

		Sec.
Loading time	=	24
Grinding time	=	175
Handling time	=	60
Checking pieces (gauge)	=	40
Wheel dressing	=	20
		319
Fatigue allowance 10 per cent.	=	32
Total time		351

This 351 sec. is for 6 components; the time for one piece would be:

$$\tfrac{351}{6} = \mathbf{59 \text{ sec.}}$$

Time per component = **59 sec. each.**

The allowance for wheel dressing is usually 10 per cent. of the cutting time; in the above case it would be 17·5 sec., but 20 sec. were assumed in this example.

For rotary grinding machines the table speeds have already been indicated, but it may be necessary to assume a mean radius on which to base the surface speed. Supposing the workpieces were placed on the table such that the components being small were between 10 in. and 20 in. diameter circles on the table, a mean figure must be found, which in this case will be:

$$\text{Mean diameter} = \frac{10 + 20}{2} = 15 \text{ in.}$$

$$\text{Mean radius} = \mathbf{7\tfrac{1}{2} \text{ in.}}$$

If the table held 22 such components, and the grinding allowance and compensation were as in the previous example, the revolutions of the table for a given feed could be obtained.

As for the reciprocating table, total allowance = 0·025 sec.

Assume a table feed of 0·002, and then the number of table revolutions can be calculated. These will be 12 at a feed of 0·002 in., plus one further revolution with a feed of 0·001 in. to make up the total of 0·025, although in many cases the 12 revolutions found will be sufficient for the purpose of calculating the grinding time.

		Sec.
Loading time	$= 22 \times 6$	= 132
Grinding time	$= \frac{12}{4} \times 60$	= 180
Handling time		= 60
Gauging		= 35
Wheel dressing		= 18
		425
Fatigue 10 per cent.		= 43
Total time		468
Time per piece	$= \frac{468}{22}$	= **21·5 sec.**

In finding the grinding time $\frac{12}{4} \times 60$, 12 is the number of table revolutions, and 4 is the number of revolutions required at $7\frac{1}{2}$ in. radius to give the required peripheral speed. This figure is mainly controlled by the speeds available on the machine.

For *cylindrical grinding* much of the calculation is done in the same manner as for surface grinding—the calculation of the cutting time is the same. The main variants are the feeds per pass and the determination of the wheel traverse. It is not proposed to give here tables of grinding allowances; the reader should refer to the tables given in the handbooks which give these details and the British Standards Specifications which deal with this subject.

Bore Grinding

The speed of the work is usually taken as 120 ft. per minute, the travel of the grinding wheel is usually two-thirds of the wheel width per revolution, the total grinding wheel travel being twice the width or length of work, plus $\frac{1}{2}$ in. (see Fig. 94).

Wheel travel per revolution = $\frac{2}{3} W$, where W = width of wheel. As a general guide the traverse per revolution of the work is as follows:

Work up to $\frac{3}{4}$ in. diameter	$= \frac{1}{3} W$
Work $\frac{3}{4}$–$1\frac{1}{2}$ in. diameter	$= \frac{1}{2} W$
Work above $1\frac{1}{2}$ in. diameter	$= \frac{2}{3} W$

The above are general figures and are modified according to class of work, but are suitable guides where no existing rules are in operation or available.

The $\frac{1}{2}$ in. allowance mentioned above is in some cases allowed at each end of the pass, and the travel then becomes:

$$\text{Travel per pass} = L - W + 2 \times \tfrac{1}{2} \text{ (external grinding)}$$
$$= L - W + 1, \text{ where } L = \text{length of work}$$

Number of passes per minute × length of one pass equals the total travel per minute.

$$\text{Total travel per minute} = \text{R.P.M.} \times W \times \tfrac{2}{3}.$$

$$\text{Number of passes per minute} = \frac{\text{R.P.M.} \times W \times \frac{2}{3}}{L - W + \frac{1}{2}} = \frac{\text{Total travel}}{\text{Travel per pass}}$$

For internal grinding, the feed per pass is generally 0·0003 in., a good guide being:

Bores up to $\frac{1}{2}$ in. diameter = 0·0001 in. feed
Bores $\frac{1}{2}$–$1\frac{1}{2}$ in. diameter = 0·00015–0·0002 in. feed
Bores above $1\frac{1}{2}$ in. diameter = 0·0002–0·0003 in. feed

The usual figure for finish grinding feed per pass is 0·0001 in.

$$\begin{array}{c}\text{Cutting time } T \\ \text{(internal grinding)}\end{array} = \frac{\text{Grinding allowance} + \text{Compensation}}{\text{No. passes per minute} \times \text{Feed per pass}}$$

$$= \frac{\text{Total metal removed}}{\text{Feed per minute}}$$

$$T = \frac{\text{Stock removed} \times L - W + \frac{1}{2}}{\text{R.P.M.} \times W \times \frac{2}{3} \times \text{Feed per minute}}$$

Similarly:

$$\begin{array}{c}\text{Cutting time} \\ \text{(external grinding)}\end{array} = \frac{\text{Grinding allowance} + C}{\text{No. passes per minute} \times \text{Feed per pass}}$$

$$T = \frac{\text{Total stock removed}}{\text{Feed per minute}}$$

Where no predetermined values of grinding allowance are given, use one of the following values depending on the diameter of work:

Up to $\frac{3}{4}$ in. diameter = 0·010
$\frac{3}{4}$–$1\frac{3}{4}$ in. diameter = 0·015
Above $1\frac{3}{4}$ in. diameter = 0·020

Large components are, of course, treated specially, and some of these have $\frac{3}{32}$ in. grinding allowance.

Wheel dressing is 10 per cent. of cutting time; fatigue allowances, 10–15 per cent., as in previous examples.

Where a grinding machine is set up for one size of component for a long run, the times can be checked. Generally, each machine is capable of taking a number of sizes, and for intensive production a machine is used for each size of component. This applies to both internal bores and external grinding.

The " Heald " grinder is a well-known bore grinding machine, and for work done on these machines the loading time, which varies with size of component, is between $\frac{1}{4}$ min. and 2 min.

For a work speed of 120 ft. per minute the revolutions of the work spindle are given by dividing the work diameter into 458 :

$$\text{i.e. work spindle r.p.m.} = \frac{458}{D}$$

Thus, for $\frac{1}{2}$-in. diameter bore, or shaft being ground, the speed of the work will be 916 r.p.m.

The size of work varies between $\frac{1}{2}$ in. diameter and $6\frac{1}{2}$ in., usually between 0·5 in. and 6·625 in., and the stock to be removed, i.e. grinding allowance, is between 0·012–0·029 in.

$$\text{Basic time} = \frac{\text{Stock to be removed}}{0{\cdot}0003} \times \frac{2 \times (\text{Work length} + \frac{1}{2}\text{ in. clearance})}{\text{R.P.M.}}$$

For a $\frac{3}{4}$-in. bore having a length of $1\frac{1}{4}$ in., grinding allowance 0·012 in., the basic time would be ·

$$= \frac{0{\cdot}012}{0{\cdot}0003} \times \frac{\frac{2 \times (1\frac{1}{4} + \frac{1}{2})}{458}}{\frac{3}{4}}$$

$$= \frac{120}{3} \times \frac{3\frac{1}{2}}{610}$$

$$= 40 \times \frac{7}{1220} \text{ min.}$$

$$= \mathbf{13{\cdot}8, \text{ say } 14 \text{ sec. approx.}}$$

The loading time will be 0·32 min. = 19·2 sec.

In some firms the allowances are catered for by a single percentage. In the above case 67 per cent. of the basic time is allowed, and this would give a figure of 23 sec.

If the loading time is added first, the figure for the above component will be:

		Sec.
Basic time	=	14·0
Loading time	=	19·2
		33·2
67 per cent.	=	22·24
Total	=	55·44

Or working out the problem another way:

$$\text{R.p.m.} = \frac{458}{0{\cdot}75} = 610$$

Feed per pass = 0·0003

$$\text{Number of passes per minute} = \frac{610 \times 1 \times \frac{3}{8}}{1\frac{1}{4}}$$
$$= 324$$

$$\begin{aligned}
\text{Grinding allowance} &= 0{\cdot}012 \\
\text{Compensation allowance} &= 0{\cdot}006 \\
\text{Total stock to be removed} &= 0{\cdot}018 \\
\text{Feed per pass} &= 0{\cdot}0003 \text{ in.} \\
\text{Cutting time} &= \frac{0{\cdot}018}{0{\cdot}0003 \times 324} \\
&= 0{\cdot}186 \text{ min.}
\end{aligned}$$

$$\begin{aligned}
\text{Cutting time} &= 0{\cdot}186 \text{ min.} \\
\text{Wheel dressing} &= 0{\cdot}0186 \\
\text{Gauging} &= 0{\cdot}1 \\
\text{Loading} &= 0{\cdot}5 \\
&\ 0{\cdot}8046 \\
\text{Fatigue} &= 0{\cdot}12 \\
\text{Total} &= 0{\cdot}9246 \text{ min.} \\
&= 55{\cdot}5 \text{ sec.}
\end{aligned}$$

Thus the two methods agree closely, giving a time of 55·44 sec. and 55·5 sec.

The compensation allowances are of the following order for bores up to 6 in. diameter ·

Coarse limits .	. 0·004 in.
General limits	. 0·007 in.
Fine limits	. 0·010 in.
Taper bores	. 0·020 in.

The average grinding allowances to cover most cases can be taken as those in the following table

TABLE 8

Bore Diameter *In.*	*Allowance* *In.*
$\frac{1}{4}$	0·004
$\frac{3}{8}$	0·005
$\frac{1}{2}$	0·006
$\frac{3}{4}$	0·007
1	0·008
$1\frac{1}{2}$	0·010
$2\frac{1}{2}$	0·012
3	0·015
4	0·017
6	0·020

Exercises on Chapter I

1. Plan the sequence of operations for making a B.S.W. (British Standard Whitworth) bolt on a capstan lathe. Bolt diameter $\frac{1}{2}$ in., 2 in. long under the head, screwed portion 1 in. long.

2. (*a*) How long will it take to turn a length of bar 2 ft. long, $2\frac{1}{2}$ in. diameter if cutting speed is 110 ft. per minute and rate of feed 84 cuts per inch ? (*b*) If the nearest spindle speed is 120 r.p.m., what additional time will be required and what is the value of the cutting speed at the lower r.p.m. of 120 ?

3. Calculate the suitable bar diameters for the following r.p.m. at a cutting speed of 100 ft. per minute : (i) 760 ; (ii) 510 ; (iii) 382 ; (iv) 190 ; (v) 127 ; (vi) 100 ; (vii) 20.

4. What would the r.p.m. be for the diameters found in Question 3 if the cutting speed were increased to 150 ft. per minute ?

5. Draw the layout of the turret and cross slide tools for the operations required in Question 1

6. List the operations and draw out the turret and cross slide tools for finishing the screwed union in Fig. 1.

7. Calculate the cutting time for drilling a component which has the following holes in it : Two 1 in. diameter $1\frac{1}{2}$ in. deep ; four $\frac{3}{4}$ in. diameter 1 in. deep ; two $\frac{1}{2}$ in. diameter $\frac{3}{4}$ in. deep ; and two $\frac{1}{4}$ in. holes $\frac{3}{8}$ in. deep, cutting speed 100 ft. per minute, feed rate (*a*) 5 in. per minute, (*b*) from Table 4.

8. Construct a table for drill sizes from $\frac{1}{16}$ in. to 1 in. diameter in increments of $\frac{1}{16}$ in. diameter, giving corresponding values of r.p.m. for cutting speeds of 100 ft. per minute.

9. (*a*) Describe the allowances made on actual cutting times, stating what contingencies they cover. (*b*) What would they be for the drilling time of Question 7 above, and what would the addition of these make the value of the time for drilling the holes in question 7 ?

10. Repeat Question 8 for cutting speeds of 40 and 60 ft. per minute for drill diameters $\frac{1}{16}$, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and 1 in. diameters.

CHAPTER II

SPEEDS AND FEEDS

In the previous chapter these quantities have been used in the determination of the time taken to perform a group of operations and in some cases single or individual operations. The whole question of metal removal hangs on this aspect, and the aim is to operate a machine at the highest rate of speed and feed that it is possible to use with safety.

Cutting speed has been referred to, and whilst a given cutting speed for a certain material does not vary, yet it is necessary to revolve the work at varying speeds in order to obtain this given cutting speed for different diameters of workpiece.

There are several ways in which cutting speed is defined. Either the tool is moved over the work as in shaping, planing, broaching, etc., or the work is moved over the tool as in turning.

Cutting speed, then, is the distance in feet that the tool moves round, over or along the material being cut in 1 min., or more briefly, it is the distance in feet that the tool or work moves past a given point per minute (see Figs. 8, 8A, and 9).

Proof of the expressions already used in Chapter I is seen by the following with reference to Fig. 8. If a bar of diameter D in. is revolving at N r.p.m. the peripheral speed or cutting speed S in feet per minute will be $S = \frac{\pi DN}{12}$.

For in one revolution the distance moved will be πD in.

$$= \frac{\pi D}{12} \text{ ft.}$$

$$\text{In } N \text{ revolutions } S = \frac{\pi DN}{12}$$

$$\therefore 12S = \pi DN$$

$$\text{and } N = \frac{12S}{\pi D}$$

Therefore, for a given cutting speed of S ft. per minute, the revolutions per minute of the machine spindle can be found for any value of D.

Now the provision of these spindle speeds is by suitable gears. On old lathes a cone pulley and back gear is used, and this type is still in existence and in everyday use in some workshops.

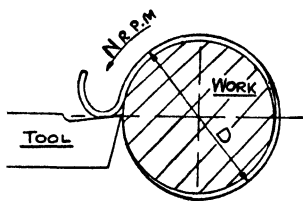
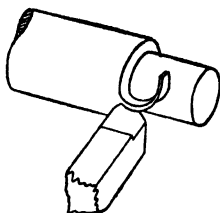
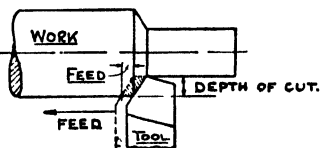



FIG. 8 FIG. 8A FIG. 9

However, the majority of machines use a range of gears which is designed in accordance with the range of work which the machine will be called upon to handle when in operation.

In the old back-geared lathe and machines using a stepped pulley for the drive, it will readily be seen that the steps between successive speeds are in arithmetical progression.

The connection between the two can be seen by referring to Fig. 10.

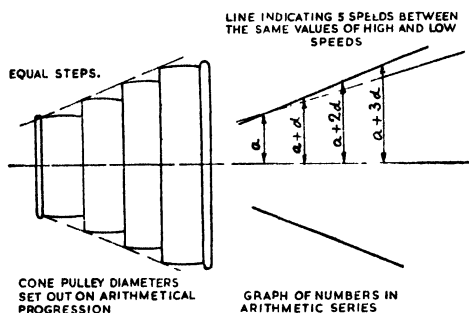



FIG. 10

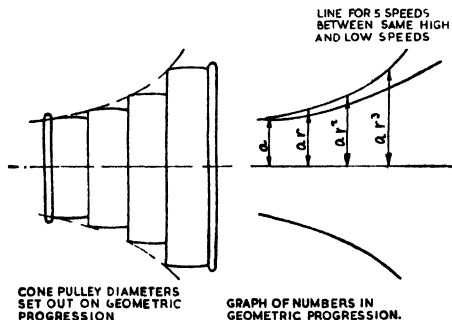



FIG. 11

In the arithmetical arrangement or progression the increases are as shown, being a ; $a + d$; $a + 2d$, etc., and the diameters of the steps on the pulleys increase in this manner. So also do some spur-gear diameters for spindle speeds. When the diameter of the work varies between two extremes, that is, a minimum diameter and a maximum diameter as in drills and lathes, the corresponding revolutions of the machine spindle to give a desired cutting speed can readily be found. These two speeds then become the maximum and minimum speeds at which the machine will run, and intermediate speeds can be decided upon for corresponding intermediate diameters of work. One method, as applied to the early speed cones, would be to take the two extreme diameters and space between them the requisite number of intermediate diameters correspond-

ing to the speeds required. From these intermediate diameters the speeds required could be calculated, and these would be in arithmetical progression.

To illustrate the point, let us take a simple example. A 6-in. lathe (12-in. swing) can obviously take a bar 12 in. diameter. If now the minimum diameter which is to be handled is 1 in., we have the two extremes fixed. Suppose the lathe is to be used for operations on steel and to allow a cutting speed of 120 ft. per minute, then the number of revolutions of lathe spindle for these two sizes will be :

$$N_{12} = \frac{12S}{\pi D}$$

$$= \frac{12 \times 120}{\pi \times 12} = \frac{120}{\pi}$$

$$\therefore N_{12} = \mathbf{38{\cdot}3\ r.p.m.}$$

$$N_1 = \frac{12 \times 120}{\pi \times 1} = \frac{1440}{\pi}$$

$$N_1 = \mathbf{459\ r.p.m.}$$

Taking these as 459 and 38 approximately, we can use them to insert any number of intermediate speeds. Let there be six speeds in all, that is, between 459 and 38 revolutions there are 4 speeds placed. The step from one speed to the next will be one-fifth of the difference between these two.

$$\text{Thus } 459 - 38 = 421$$

$$\text{Interval between speeds} = \tfrac{421}{5}$$

$$= \mathbf{84\ approx.}$$

Hence first speed = 38 and the second speed will be 38 + 84 = 122 r.p.m. and the third speed will be 122 + 84 = 206 r.p.m., and so on up to 458 r.p.m.

1st speed as found = 38 r.p.m.
2nd speed = 38 + 84 = 122 r.p.m.
3rd speed = 122 + 84 = 206 r.p.m
4th speed = 206 + 84 = 290 r.p.m.
5th speed = 290 + 84 = 374 r.p.m.
6th speed = 374 + 84 = 458 r.p.m.

Now from these figures it can readily be seen that there is too big a gap at the slower speeds and the step should not be as great as 84 r.p.m., as this does not allow sufficient variation, and as can be seen from the sketch of the cone pulley, this range of speeds lies on a straight line and follows the law of arithmetic progression.

Again, the difference between the first and second speed, although the same as that between the fifth and last, nevertheless has a greater effect when the corresponding bar or work diameters are calculated.

For instance, 38 r.p.m. corresponds to the 12 in. diameter and

$D = \frac{12S}{\pi N}$, from which we can find the diameter corresponding to 122 r.p.m., which will be:

$$D_1 = \frac{12 \times 120}{\pi \times 122} = \frac{1440}{122\pi}$$

$$D_1 = \mathbf{3{\cdot}76\ in.}, \text{ say } \mathbf{3\tfrac{3}{4}\ in.\ diameter.}$$

For 458 r.p.m. the diameter is 1 in., and the nearest speed to this being 374 corresponds to:

$$D_2 = \frac{1440}{\pi \times 374}$$

$$\text{i.e. } D_2 = \mathbf{1{\cdot}23\ in.}, \text{ say } \mathbf{1\tfrac{1}{4}\ in.\ diameter.}$$

Now it is at once apparent that the first two speeds, viz. 38 and 122, must be closer together if the cutting speed is to be reasonably observed, because there is a difference of 8¼ in. in the respective diameters between these two consecutive speeds.

On the other hand, at the other end of the speed range the difference in the work diameters is only ¼ in. approximately—a difference that is in many instances equal to the variation in size of a piece before and after finishing, i.e. before and after a cut has been taken.

It will be agreed, therefore, that at the lower speeds a closer interval is required and at the higher speeds a greater interval can well be accommodated.

Relating this to our cone pulley, it means that the difference in diameters must be small at the lesser end and greater at the large end. This point is clarified in Fig. 11, which exaggerates the condition.

From these sketches it will be evident that if the first speed is a, then the second speed is a times some ratio, say r, $= ar$. The third speed will be ar times the ratio, and becomes $ar \times r = ar^2$ and so on, the sixth speed being ar^5. This is the well-known Geometrical Progression, and speeds arranged on this basis are much more practical than a range set on the arithmetical series.

The effect of these two methods is apparent in this example. As for the first part, we start with the two extreme speeds as calculated, viz. 38 and 458 r.p.m., and using the notation for a G.P. (Geometrical Progression), we have:

1st speed, $a = 38$
2nd speed, $ar = 38r$
3rd speed $= 38r \times r = 38r^2$, and so on.
6th speed, $ar^5 = 458$
From this $38r^5 = 458$
$r^5 = \frac{458}{38}$

and from this expression it is easy to find the value of the common ratio r

$$\text{since } r^5 = \tfrac{458}{38}$$
$$r = \sqrt[5]{\tfrac{458}{38}}$$
$$= \sqrt[5]{12{\cdot}05}$$
$$r = \mathbf{1{\cdot}645}$$

Thus the speeds can be found by multiplying 38 r.p.m. by r, r^2, r^3, r^4, and r^5, and if we tabulate these speeds and place the first set of values worked out on the arithmetic basis against those worked out on the geometric basis, the difference will be clearly apparent.

Speeds worked out on the Geometric Basis	*Speeds worked out on the Arithmetic Basis*
1st speed = a = 38 = 38 r.p.m.	1st speed = 38 r.p.m.
2nd speed = ar = 38 × 1·645 = 62·52 r.p.m	2nd speed = 122 r.p.m.
3rd speed = ar^2 = 62·5 × 1·645 = 102·8 r.p.m.	3rd speed = 206 r.p.m.
4th speed = ar^3 = 102·8 × 1·645 = 169·2 r.p.m	4th speed = 290 r.p.m.
5th speed = ar^4 = 169·2 × 1·645 = 278·4 r.p.m	5th speed = 374 r.p.m.
6th speed = ar^5 = 278·4 × 1·645 = 458 r.p.m	6th speed = 458 r.p.m

Now the speeds 38, 63, 103, 169, 278, 458 are a much better arrangement for dealing with work diameters within the capacity of the machine, and no doubt the final selection would be somewhat after the following :

1st speed 38 or 40 r.p.m. as against 38 or 40 r.p.m.
2nd speed 63 or 65 r.p.m. as against 122 or 125 r.p.m.
3rd speed 103 or 105 r.p.m. as against 206 or 210 r.p.m.
4th speed 169 or 170 r.p.m. as against 290 or 295 r.p.m.
5th speed 278 or 280 r.p.m. as against 374 or 375 r.p.m.
6th speed 458 or 460 r.p.m. as against 458 or 460 r.p.m.

If the values of the speeds were plotted with speeds as ordinates, the difference between the two ranges would be clearly emphasised, as in Fig. 12.

Since the Geometric Speed Range is most frequently used, the method of dealing with it can be summarised thus :

After finding the two extreme speeds, the highest and the lowest, the next step is to find the ratio or factor by which successive speeds must be multiplied in order to complete the range.

If n be the number of speeds.
If H be the highest speed.
If L be the lowest speed.

$$\text{Ratio } r = \sqrt[n-1]{\frac{H}{L}}$$

For 8 speeds in the range:

$$r = \sqrt[8-1]{\frac{H}{L}} = \sqrt[7]{\frac{H}{L}}$$

The above method can be applied to gears for other machines, such as milling machines and drilling machines, and a further example will now be given.

Suppose a drilling machine is to be designed for drilling holes between $\frac{1}{8}$ in. and $\frac{7}{8}$ in. diameter, and is to have ten speeds in all. The cutting

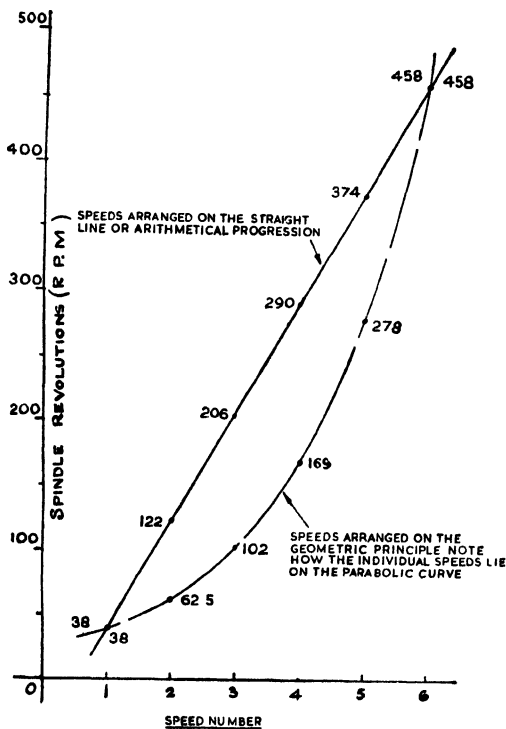



FIG. 12

speed is to be 100 ft. per minute for medium cast iron and mild steel. Determine the necessary ten speeds, and then tabulate the results, including the approximate drill sizes applicable to each speed.

As in the first example

$$N_L = \frac{12S}{\pi D}$$

$$= \frac{12 \times 100}{\pi \times \frac{7}{8}} = 430$$

$$N_L = 430 \text{ r.p.m.}$$

$$N_H = \frac{1200}{\pi \times \frac{1}{8}}$$

$$= \frac{9600}{\pi} = 3000$$

$$N_H = \mathbf{3{,}000\ r.p.m.}$$

Now from what has already been said and the deductions made from the comparisons of the arithmetic and geometric ranges, it is obvious that the 10 speeds will be arranged in geometric progression ·

$$\text{The multiplying factor } r = \sqrt[n-1]{\frac{H}{L}}$$

where n = number of speeds in the range.
H = high speed.
L = low speed.

$$\text{Then } r = \sqrt[10-1]{\frac{3000}{430}}$$

$$= \sqrt[9]{6{\cdot}976}$$

$$r = \mathbf{1{\cdot}241.}$$

Taking, then, the lowest speed of 430 r.p.m. and multiplying it by 1·241, will give the second speed, which in turn when multiplied by 1·241 will give the third speed, and so the range of speeds can be built up.

1st speed = a		=	430 r.p.m.
2nd speed = ar	= 430 × 1·241	=	533 r.p.m.
3rd speed = ar^2	= 533 × 1·241	=	662 r.p.m.
4th speed = ar^3	= 662 × 1·241	=	821 r.p.m.
5th speed = ar^4	= 821 × 1·241	=	1,024 r.p.m.
6th speed = ar^5	= 1024 × 1·241	=	1,272 r.p.m.
7th speed = ar^6	= 1272 × 1·241	=	1,577 r.p.m.
8th speed = ar^7	= 1577 × 1·241	=	1,956 r.p.m.
9th speed = ar^8	= 1956 × 1·241	=	2,427 r.p.m.
10th speed = ar^9	= 2427 × 1·241	=	3,000 r.p.m.

(Actual figure is 3,006, due to error of continued multiplication by 1·241 which may not be quite accurate.)

Now 430 r.p.m. corresponds to $\frac{7}{8}$ in. diameter and 3,000 r.p.m. to $\frac{1}{8}$ in. diameter, and the intermediate speeds will correspond to various diameters which can be found as follows ·

Since 533 r.p.m. is 1·241 times 430 r.p.m., the drill size corresponding to 533 r.p.m. will be $\frac{1}{8}$ times 1·241, this gives 1·241 × 0·125

$$= \mathbf{0{\cdot}155\ in.}$$

Similarly, the next size will be 0·155 × 1·241 = 0·1923 in. and so on up to $\frac{7}{8}$-in. diameter drill

For the sake of clarity the values of the speeds and their corresponding drill sizes may be placed in tabular form as shown below, and this will serve as a guide for an indicator plate to be placed on the machine.

Spindle r.p.m.	3,000	2,420	1,950	1,575	1,272	1,024	821	662	533	430
Drill size (decimal), in.	0·125	0·155	0·1923	0·2385	0·2959	0·3670	0·4553	0·5648	0·7030	0·875
Drill size (fraction), in.	$\frac{1}{8}$	$\frac{5}{32}$	$\frac{3}{16}$	$\frac{15}{64}$	$\frac{19}{64}$	$\frac{25}{64}$	$\frac{29}{64}$	$\frac{9}{16}$	$\frac{45}{64}$	$\frac{7}{8}$

When the spindle speeds have been settled as above, the details regarding the gears required can be settled, such as diameter, pitch, number of teeth, etc., in order to complete the gearbox.

In some cases the gears arrived at by this method are in the form of a cone similar to the cone pulley, and the different speeds obtained by using a constant-size wheel to pick up the drive from the individual gearwheels corresponding to the sizes. Problems of this nature sometimes occur, and a final example will be dealt with to illustrate this point. It should be clear at this stage that once the two limits of feed for a machine are fixed, that is to say the coarsest and finest feeds desirable on any particular machine, the intermediate range or the intermediate feeds between these two extremes can be obtained in the same manner as those just dealt with.

The example which follows could well apply to the feed cone used in the feed gearbox of a lathe, of which there are a great many in existence, although there is now a tendency for a preselector or preoptive type of gearbox to be used for both spindle speeds and cutting feeds and in some cases for cross feed. These recent methods are most effective in reducing to a minimum the time required to produce a component, at the same time maintaining high accuracy and surface finish.

A feed box for a lathe is to provide six feeds in G.P. with a ratio of $\sqrt{2}$, using a feed cone with six gears on the driving shaft. The lowest driven speed is to be 20 r.p.m. and the constant speed shaft driving the cone makes 60 r.p.m. If the number of teeth in the drive shaft is 25 and all teeth are 10 diametral pitch, calculate the remaining speeds and the number of teeth in each gear.

$$\text{Gear ratio} = \sqrt{2} = 1{\cdot}414.$$

$$\text{Ratio for lowest speed} = \frac{60}{20} = 3 \text{ to } 1.$$

$$\text{Diameter of drive shaft gear} = \frac{\text{Number teeth}}{DP} = \frac{25}{10} = 2{\cdot}5 \text{ in}$$

$$\text{Number of teeth in lowest driven gear} = 25 \times 3 = 75$$

$$\text{Diameter of this gear} = \frac{75}{10} = 7{\cdot}5 \text{ in.}$$

$$\text{Centre distance of gears} = \frac{7{\cdot}5 + 2{\cdot}5}{2} = \frac{10}{2} = 5 \text{ in.}$$

The remaining speeds can be calculated as in the previous examples, lowest speed = 20 r.p.m.

Speed No.	*R.P.M.*	*Number Teeth*	*T*	*Diameter In.*
1	20 = 20	75	= 75	7·5
2	20 × 1·414 = 28·28 = 28	$\frac{75 \times 20}{28}$ = 53·5	= 54	5·4
3	28 × 1·414 = 39·512 = 40	$\frac{75 \times 20}{40}$ = 38	= 38	3·8
4	40 × 1·414 = 56·56 = 56	$\frac{75 \times 20}{56}$ = 26·8	= 27	2·7
5	56 × 1·414 = 78·184 = 78	$\frac{75 \times 20}{78}$ = 19·2	= 19	1·9
6	78 × 1·414 = 110·292 = 110	$\frac{75 \times 20}{110}$ = 13·62	= 14	1·4

It will be seen that the number of teeth has had to be approximated, as the actual number resulting from the calculation is a fraction in some cases, and fractional teeth cannot be cut. The percentage error in the speeds or feeds thus resulting can be found. Also, since the centre distance between the gears at one end of the scale is 5 in., an idler must be used to connect the constant speed drive shaft with the individual gears of the speed cone. For this example the minimum size of the idler gear wheel will be $\frac{2{\cdot}5 + 1{\cdot}4}{2} = \frac{3{\cdot}9}{2} = 1{\cdot}95$ in. centre distance as against 5 in. at the other end of the speed cone. Therefore, an idler to connect between 5 in. and 1·95 in. centre distances will be 5—1·95 in. = 3·05 in., say 3 in. giving a wheel having 30 teeth.

Feed

In this section the factors affecting feed are considered. The illustration shown in Fig. 12A indicates a feed of 0·008 in., and it will be seen that the finish is a good one. The enlarged view of the work shows the feed marks to a magnified scale, and the regularity of these is a good testimony to the machine on which this piece was turned. The spindle revolutions per

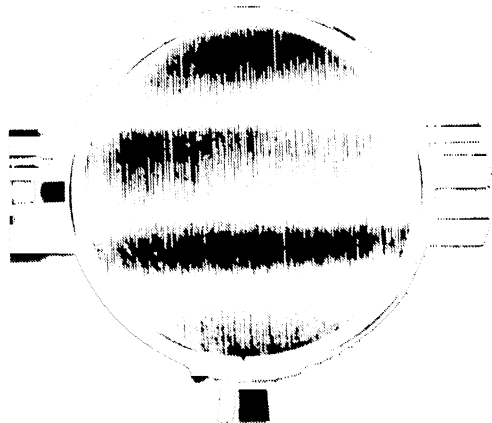



FIG 12A

minute for this work were 2,800, depth of cut $\frac{1}{16}$ in. (0·0625), and feed *0·008—i.e. eight thousandths of an inch.*

As will be evident from Fig. 18, the term feed indicates the amount of longitudinal movement of the tool on the work, or work relative to the tool. It is expressed as " cuts per inch " or revolutions per inch. Thus, in Chapter I the feed of 48 cuts per inch used in the turning example for cutting time calculation means that the tool will travel $\frac{1}{48}$ in. for each revolution of the spindle, or 1 in. for 48 revolutions of the spindle.

Therefore, the relationship between tool travel spindle speed and feed is:

$$\text{Tool travel per minute} \quad \frac{\text{Spindle R.P.M.}}{\text{Feed in cuts per inch}}$$

$$\text{Feed} = \frac{\text{Spindle R.P.M.}}{\text{Tool travel per minute}}$$

A definite figure cannot be given for feed, nor can the above expression be used to determine speed or feed in a general sense. The depth of cut governs the amount of feed, and the power of the machine, its rigidity, and similar factors limit the amount of both, since these two factors control the amount of metal removed per minute or per horse-power. Feed multiplied by depth of cut and cutting speed will give the volume of material removed per minute, i.e.:

$$\text{Stock removed, cubic inches per minute} = D \times F \times S$$

From this consideration it is better to consider the area of cut, which is Depth $D \times$ Feed F. Now for a machine of given power it is apparent that there will be a maximum value for area of cut A, and if this is taken as a constant, then, since $A = D \times F$, it is obvious that if D increases F must decrease.

For a given depth of cut, then, the high limiting factor for the feed will be the power available on the machine, whilst at the other end of the scale the low limiting factor will be the finish required on the work. Generally speaking, the finer the feed the better the surface finish on the work, and for roughing cuts the maximum amount of depth of cut and feed are taken in order to reduce the workpiece to within the limits of size allowed for the finishing operation. When a piece has been rough machined, the amount of metal left for removal is small and the finishing is done at a higher speed, and although from a consideration of the relationship, $D \times F$, for a small value of D the corresponding feed F may be reasonably large, the feed is kept small and a fine feed used.

It is also customary in some cases to have a semi-finishing cut which is between a roughing cut and a finishing cut proper, and in such instances the material is machined up in this manner where quality of finish and fine limits of size are not required, as is the case in certain classes of outdoor machinery and heavy work.

The increasing use of negative rake tools and tungsten carbide tips has allowed greater cutting speeds, and has resulted in a good surface finish being obtained with material machined up at speeds, depth of cut, and rates of feed hitherto unheard of. This method of machining requires more power than conventional machining methods and definite rigidity of tool and machine, so that the older types of machine are unsuited to this work either due to lack of rigidity or insufficient power.

For turning and boring, the feeds for tipped tools should be 20–25 per cent. finer than for high-speed steel tools, but the cutting speed can be increased by 250–300 per cent.

Average values for feeds vary both with the material being machined and the size of the machine, but for cast iron 20–40 cuts per inch and for steel 40–80 cuts per inch are generally applicable.

The variation of this quantity can be seen from the feed rates available on various types of lathes being as low as 4 cuts per inch, giving $\frac{1}{4}$-in. feed, and as high as 1,000 cuts per inch or 0·001-in. feed.

In some cases it is advisable in practice to start with fine feed, i.e. finer than conditions would seem to demand, and work up to the coarser feeds, and similarly with cutting speeds. Trial cuts at finer feeds and lower cutting speeds should be tried out, and these gradually increased until optimum conditions are reached.

As a point of interest, illustrating the variety of feed rates for surfacing and sliding provided on present-day machines, the following values are noteworthy :

Sliding Feeds	*Surfacing (Cross Feeds)*
12–168 cuts per inch	22–1,040 cuts per inch
20–240 cuts per inch	14–1,600 cuts per inch
48–336 cuts per inch	
29–412 cuts per inch	
11–520 cuts per inch	
20–640 cuts per inch	
14–800 cuts per inch	
16–900 cuts per inch	

As the name implies, surfacing is the cutting or facing operation performed when the lathe tool moves across the end of the bar or workpiece ; it is more commonly known as " Cross Feed."

The above feeds are in cuts per inch of travel of lathe tool, giving an extreme range of $\frac{1}{11}$–$\frac{1}{900}$ in. sliding feed and $\frac{1}{14}$–$\frac{1}{1600}$ in. surfacing feed, and are directly obtainable from the feed gearboxes of the machines, other feeds, of course, being available by using change gears.

The whole question of cutting speed and feed is bound up with the question of tool life. High values of cutting speed and rates of feed can be obtained, but the tool cutting edge is destroyed in a short time and requires regrinding Speed is the vital factor governing tool life.

The relationship between cutting speed and tool life is of the order:

$$ST^n = C$$

$$\text{or } VT^n = C, \text{ a constant.}$$

This relationship between tool life T, which is usually given in minutes for calculating purposes, although it can be expressed in hours, cutting speed S in feet per minute, the index n and the constant can be applied thus:

The generally accepted figures for cemented carbide tools operating on mild steel is $\frac{1}{5}$ for n and 300 for the constant C, although higher values up to 320 are sometimes used.

Thus, for carbide cutting tools the relationship is given by:

$$VT^{\frac{1}{5}} = 300$$

For high-speed steel tools under similar conditions the relationship becomes:

$$VT^{\frac{1}{8}} = 200$$

The results given by the above expressions should be reliable guides for estimating tool life, and the modified values of the index n given later will cover some of the remaining cases.

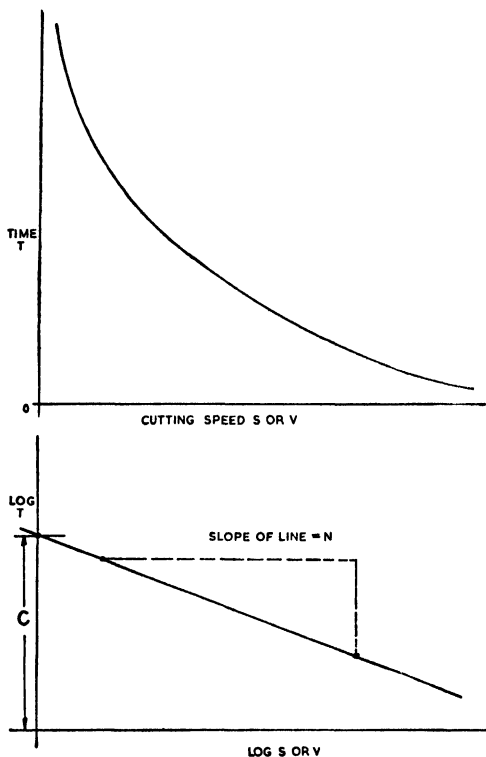



FIG. 13

In tests on the effect of cutting speed on tool life conducted in a class studying the effects of changing variables such as speed, feed, rake angle, tool material, etc., the results obtained give a curve of the order shown in the graph, Fig. 13.

The details were:

Material cut . .	Mild steel, 5·2 in. diameter
Depth of cut . .	0·05 in. kept constant
Feed . . .	0·0119 in. kept constant
Speeds . . .	25, 42, 78, 125, 160, 200, 254, 375

$$\textit{The cutting speed} = \frac{12S}{\pi D} = \text{r.p.m.}$$

and for 25 r.p.m. $S = 33{\cdot}9$

$$S = \mathbf{34\ ft./min.}, \text{ say.}$$

$$\text{For 375 r.p.m. } S = \frac{375 \times 5{\cdot}2\pi}{12} = 510{\cdot}8$$

$$S = \mathbf{510{\cdot}8\ ft./min.}, \text{ say } \mathbf{511\ ft./min.}$$

The cutting tool was of high-speed steel with standard clearance and 10° top rake angle, and all the cutting was performed dry, no coolant being used. The tool failed in approximately 5 sec. when operating at 375 r.p.m. or 511 ft. per minute, the cutting edge burning and breaking down shortly after the commencement of the cut. The curve for tool life plotted against cutting speed gives a curve of the order shown in Fig. 13, and if a set of values be used and log T be plotted against log S, a straight line should result, the slope of which will give the value of n and the intercept the value of the constant C, since:

$$\log S + n \log T = \log C.$$

The value of n obviously varies with the material being cut and the tool material. Approximate values for n are between $\frac{1}{6}$ and $\frac{1}{8}$, and about $\frac{1}{5}$ for carbide-tipped tools when cutting mild steel.

Example.—A cutting tool working on mild steel gives an average life of 3 hours between regrindings when operating at 120 ft. per minute. What will its life be if the speed is increased to 150 ft. per minute, and at what cutting speed would it have to work if it had to last throughout a complete working shift necessitating 6 hours' cutting time?

For the mild-steel material the value of n will be $\frac{1}{8}$.

$$\text{Thus } ST^{\frac{1}{8}} = C$$

$$120 \times 180^{\frac{1}{8}} = C$$

$$\text{or } 120 \times \sqrt[8]{180} = C$$

$$\text{Thus } C = 120 \times 1{\cdot}914$$

$$\therefore C = 229{\cdot}68$$

$$= \mathbf{230}$$

$$\text{Therefore } ST^{\frac{1}{8}} = \mathbf{230.}$$

To find T when S changes to 150 ft. per minute

$$150\, T^{\frac{1}{8}} = 230$$

$$T^{\frac{1}{8}} = \tfrac{230}{150} = \tfrac{23}{15}$$

$$T^{\frac{1}{8}} = 1{\cdot}533$$

$$\therefore T = 30{\cdot}54$$

i.e. the tool life would be reduced to 30·5 min. or $\frac{1}{2}$ hour.

The method is similar for the remainder of the question.

$$ST^{\frac{1}{8}} = 230$$

$$\therefore S = \frac{230}{(60\times 6)^{\frac{1}{8}}} = \frac{230}{360^{\frac{1}{8}}} = \frac{230}{2{\cdot}086}$$

$$S = \mathbf{110\ ft./min.}$$

Thus it is seen that by reducing the cutting speed from 120 to 110 ft. per minute the expected life is doubled, and by increasing it to 150 ft. per minute the life is reduced to one-sixth.

The treatment of problems involving cutting speed and tool life can be solved by the above method, the values of n being between $\frac{1}{5}$ for cemented carbides on steel; $\frac{1}{6}$–$\frac{1}{8}$ for H.S.S., taking general cuts on steel; $\frac{1}{10}$ for light finishing cuts, and $\frac{1}{12}$ for H.S.S. working on cast-iron parts.

Other tests concern the value of clearance and rake angles, and one such test gave very satisfactory confirmation of the recommended value of the top rake angle for use when cutting mild steel.

The data is as follows:

The material cut was a mild-steel billet 5·125 in. diameter, depth of cut $\frac{1}{10}$ in. = 0·10 in.

Spindle speed = 78 r.p.m.
Cutting speed, S = 105 ft. per minute
Feed per revolution = 0·0119 in.
or Feed = 84 cuts per inch = $\frac{1}{84}$ in. = 0·0119 in.

Cutting tools: high-speed steel.
Standard clearances, but top rake varying from 0–40°.

The machine used was a centre lathe, and a wattmeter was fitted in order to record the power used. This was obtained by first noting the current used to drive the lathe as used for the test, with feed operating and work revolving, but no cut in operation. Then the cut was taken, and the reading of the wattmeter for the various values of rake angle recorded.

The values obtained when plotted give a curve as shown in Fig. 14, and from this it

TOP RAKE ANGLE°	POWER K W
0	1 4
10	·92
15	78
20	·70
30	·62
40	·60

Fig. 14

TOP RAKE

SIDE TOP RAKE

CUTTING ANGLE

TRUE TOP RAKE.

FRONT CLEARANCE

SIDE CLEARANCE

TRUE CUTTING ANGLE.

"X"

FACE ANGLE.

NOSE ANGLE

SECTION ON PLANE. XX.

"X"

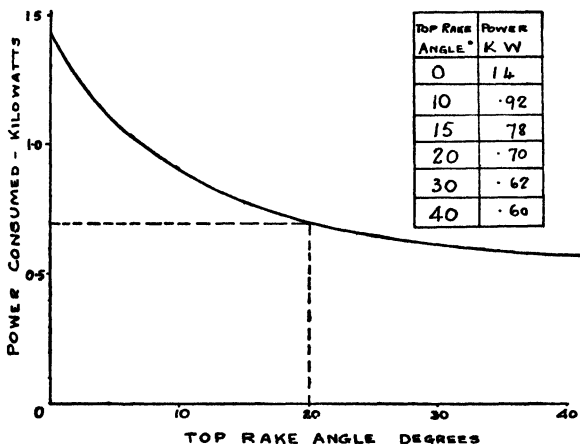
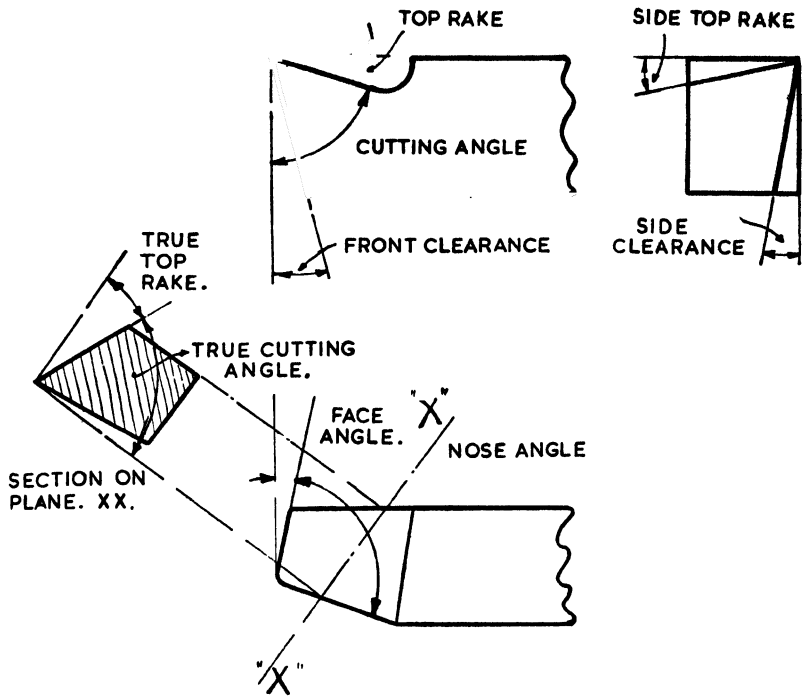
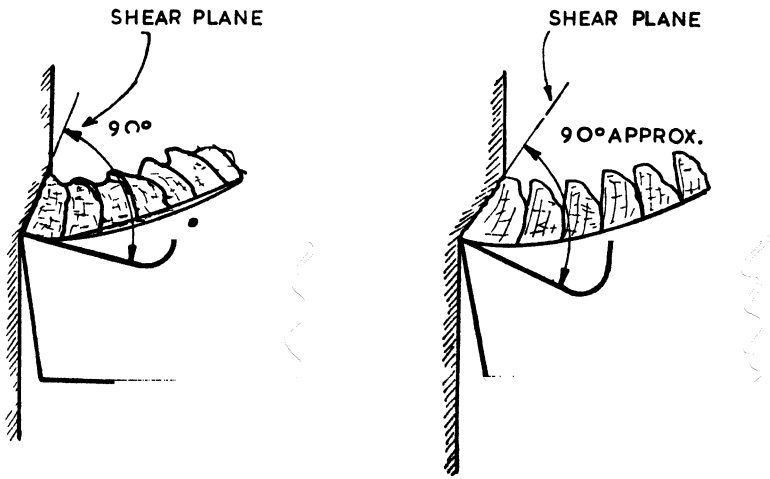
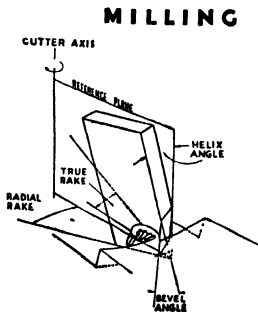
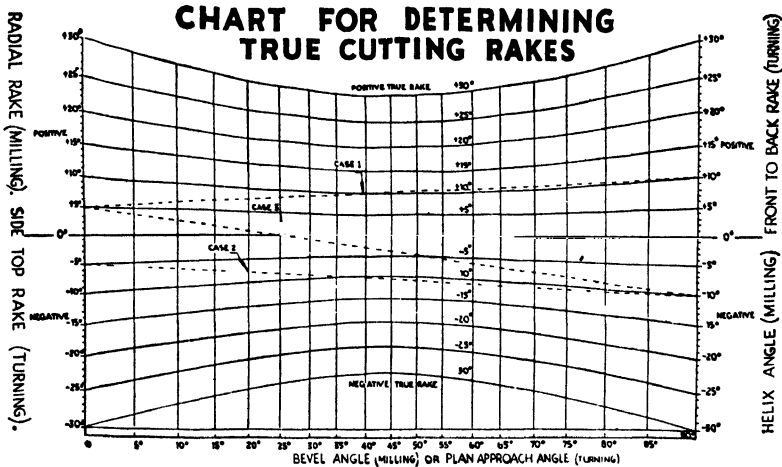



Fig. 15a

Fig. 15b

will be seen that the power used is high at 0° rake and low at 40°. At about 20° rake the curve flattens out, and the amount of saving in power is small, being 0·1 kW. between 20° and 40° rake angle. Since the saving in power consumption is small, there is no advantage in having a finer angle than 20°, as the consequent reduction in the tool section renders this very weak at 40° and accelerates the tool wear,

CASE 1.

Given - a radial rake of +5° and a helix angle of +10°;
Required the bevel angle which will give a true rake of +10°.
Solution The point of intersection between the straight edge (dotted line) and the +10° rake line falls between the 35° and 40° bevel angle vertical lines (arrow) indicating about 37° for the required bevel angle.

CASE 2

Given a radial rake of -5°, a helix angle of -10° and a bevel angle of 20°;
Required. the true rake.
Solution. The point of intersection between the ruler's edge and the 20° bevel angle line falls between the -5° and -10° rake lines (arrow) indicating that the true rake is approximately -8°.

CASE 3.

Given: a radial rake of +5° and a helix angle of -10°;
Required the range of bevel angles which will result in negative true rakes.
Solution The ruler's edge dips below the zero rake line at the 26° bevel angle line (arrow), indicating that the true rake will be negative for any bevel angle greater than 26°.

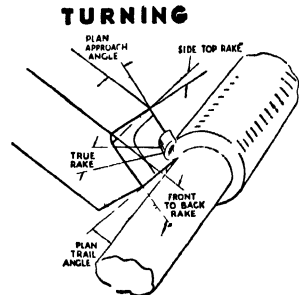



FIG. 16

and the slight advantage in power saving is more than offset by the extra tool wear and breakage, resulting in regrinding and replacement of tools.

Cutting Tools

The cutting tools themselves vary in shape according to the work they perform and the type of material cut, and are known by names usually compounded of these two functions, such as round-nose rougher, or round-nose roughing tool which, as the name suggests, refers to a tool with a round nose or point and is used for roughing cuts. Other names, such

as face and radius tool, boring tool, finishing, undercutting, recessing, and facing, all indicate the work for which the tools are designed.

The cutting tools are provided with angles, known as front clearance, side clearance, side rake, and top rake angles, the angle of the tool between the top face and the work being known as the cutting angle. These angles are shown in Figs. 15 and 16.

The shape of the tool affects the metal removal, and the condition of the material being machined influences the tool shape. Thus, for a material with hard skin, such as a steel casting, cast iron, and certain forgings, the shape of the tool will be of the form shown, in which a minimum length of cutting edge is in contact with the work to reduce damage to the tool. In this connection it is advisable to shot blast the parts before machining, as this will reduce tool wear and enable deeper cuts or bigger feeds to be used than would be the case otherwise. Fig. 16 shows the blades of a milling cutter and their action in removing metal.

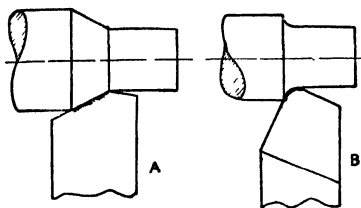
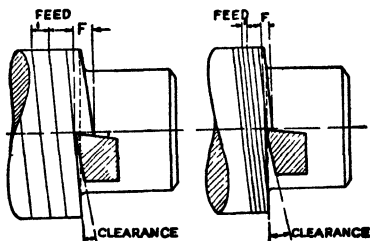



FIG. 17 FIG. 18

Where the work is reasonably soft, a maximum length of cutting edge can be used for any given depth of cut. This condition is shown in Fig. 17 (A).

For tipped tools the angles are usually different. In many cases negative rakes are used. A chart showing the operation of these tools and the method of determining the true cutting rakes is shown in Fig. 16.

The side-clearance angle is affected by the rate of feed, as the coarser this becomes the more the angle of the helix of the cut on the work approaches the side-clearance angle on the tool and causes it to rub. Rubbing is frequently caused by this means, and the clearance angles and rates of feed should be carefully considered if maximum cutting efficiency is to be obtained. The effect of the feed rate on the side-clearance angle, which is reduced as the feed becomes coarser, is shown in Fig. 18.

For this condition 4–6° side rake should be sufficient for normal or general conditions, and for undercutting, recessing, and parting tools, a side clearance of 2–3° is usually sufficient, since the tool is fed directly into the work, and does not therefore have any helix angle.

Another case where rubbing occurs is when the tool is not correctly located on the centre line of the work. The position of the tool affects the value of the clearance angle. If it is above the work centre the

clearance diminishes, and there is a point at which it disappears completely, and the tool will not cut but only rub on the surface of the work. Conversely, if it is below the centre it will increase the clearance between the front face of the tool and the work, as is shown in Fig. 19.

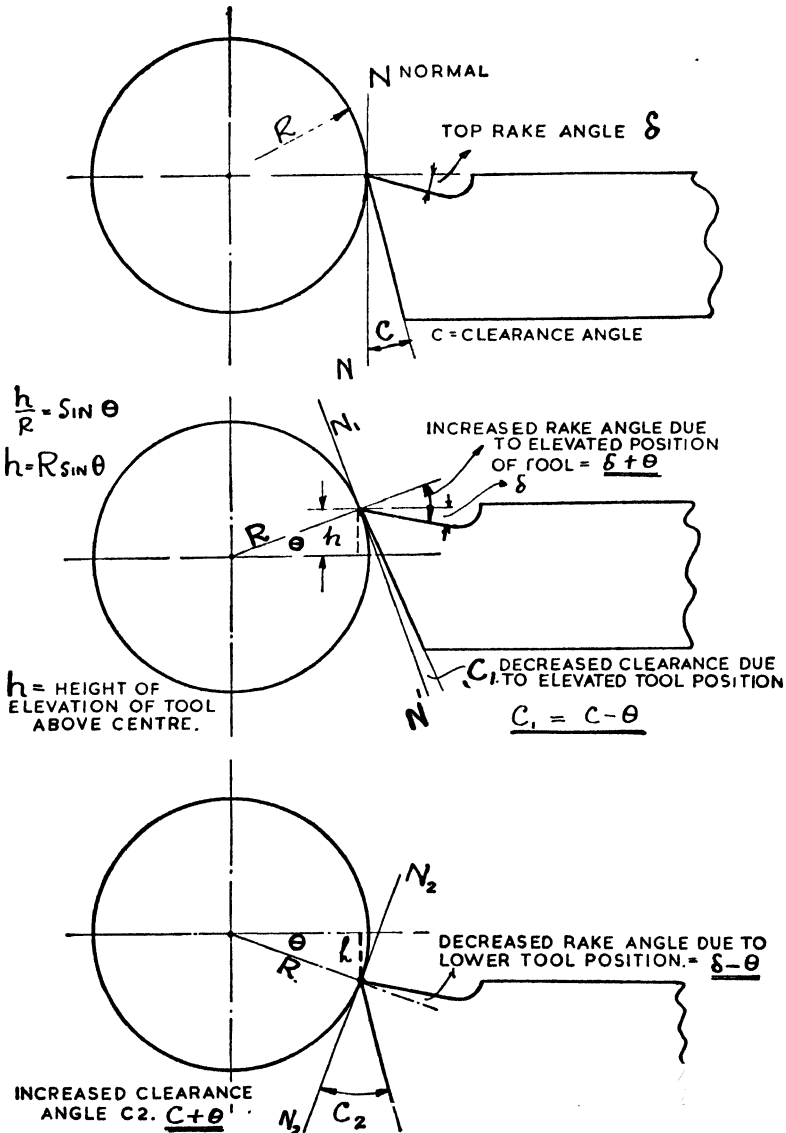



Fig. 19

It will readily be seen that the points just mentioned will all have an effect on the power required to take a cut of given depth and feed, and if allowed to remain would be detrimental to efficient cutting. They could offset any advantage gained by using the correct value of rake angle.

It was seen earlier that the power consumed varied with the angle of top rake. From a consideration of this power consumption, the tangential force on the tool when cutting can be calculated. Referring to Fig. 7 it will be seen that the work done during one revolution of the work against the cutting force P will be:

$$\text{Work done per revolution} = 2\pi RP \qquad \left[\text{where } R = \frac{D}{2}\right]$$

$$\text{For } N \text{ r.p.m. work done} = 2\pi RNP$$
$$= 2\pi NPR$$

But PR = Torque T

$$\therefore \text{ Work done} = 2\pi NT$$
$$= \pi DNP$$

(ft. lb or in. lb., depending on whether R is in feet or inches.)

Thus the horse-power equivalent of this work

$$\text{h.p.} = \frac{2\pi NT}{33000} = \frac{\pi DNP}{33000}$$

Now 1 h.p. equals 746 watts = 0·746 kW.

$$1 \text{ h.p.} = 0{\cdot}746 \text{ kW.}$$

$$1 \text{ kW} = \frac{1}{0{\cdot}746} = 1{\cdot}34 \text{ h.p.}$$

From the expression above for horse-power we get

$$T = \frac{\text{H.P.} \times 33000}{2\pi N}$$

$$\text{and since } T = PR$$

$$P = \frac{\text{H.P.} \times 33000}{2\pi NR} = \frac{\text{H.P.} \times 33000}{\pi DN}$$

Substituting for horse-power:

$$P = \frac{\text{kW} \times 33000 \times 12}{0{\cdot}746 \times \pi DN}$$

By using one or other of these equations, the value of the tangential force on the cutting tool can be found.

There is another way of approach to the problem:

$$\text{h.p.} = \frac{\text{kW}}{0{\cdot}746} = \frac{\pi DNP}{33000 \times 12}$$

$$\text{and nominal pressure } P_n = \frac{P}{\text{depth} \times \text{feed} \times 2240}$$

Example.—A mild-steel billet 4 in. in diameter is being turned between lathe centres, and the cut consumes power which is measured by a recording wattmeter. If the power consumed when the machine is running light, i.e. without the cut, is 0·35 kW, and 1·65 kW when actually cutting, what depth of cut could be taken with a feed of 0·01 in. if the nominal pressure on the tool is restricted to 100 tons per square inch? Take the cutting speed to be 110 ft. per minute.

First we find the tangential force:

$$\text{h.p.} = \frac{\pi DNP}{33000 \times 12} = \frac{\text{kW}}{0{\cdot}746}$$

$$\therefore P = \frac{\text{kW} \times 33000 \times 12}{\pi DN \times 0{\cdot}746}$$

$$= \frac{(1{\cdot}65 - 0{\cdot}35) \times 33000 \times 12}{\pi \times 4 \times 0{\cdot}746 \times N}$$

To find N from cutting speed:

$$N = \frac{12S}{\pi D}$$

$$= \frac{12 \times 110}{\pi \times 4}$$

$$N = \mathbf{105{\cdot}5\ r.p.m.}$$

Substitute in the equation above the value 105·5 r.p.m. for the revolutions of the work spindle:

$$P = \frac{1{\cdot}3 \times 33000 \times 12}{\pi \times 4 \times 0{\cdot}746 \times 105{\cdot}5}$$

$$\therefore P = \mathbf{520\ lb.}$$

The nominal pressure on the tool, P_n, is given by the equation:

$$P_n = \frac{\text{Tangential force}}{\text{Area of cut} \times 2240}$$

$$P_n = \frac{P}{D \times F \times 2240}$$

Now P_n must not exceed 100 tons per square inch

$$\therefore 100 = \frac{520}{D \times 0{\cdot}01 \times 2240}$$

$$\text{i.e. } 100 \times D \times 0{\cdot}01 \times 2240 = 520$$

$$\therefore D = \frac{520}{100 \times 0{\cdot}01 \times 2240}$$

$$D = \mathbf{0{\cdot}232\ in.}$$

From the foregoing it will readily be seen that any one of the variables can be found when the others are known, and a number of values for

feed, depth of cut, or tangential force can be presumed and the variable quantity calculated for the assumed values.

The value of P_n, nominal pressure on the tool point, seems high, but this will be understood when it is realised that a relatively small tangential force of say 100 lb. is acting on a small area—the area of cut which is depth times feed. This small area divided into the tangential force gives a high value to the nominal pressure, and obviously is a contributing factor to the tool life.

In some cases, where the area of cut is used in the calculation of the pressure or load on the tool point, a factor is employed, and for the conditions obtaining in this problem the value of this factor which corresponds to the nominal pressure is given as 115 tons per square inch or 120 tons per square inch for use in finding cutting pressure on tool. (See Table 9 for area of cut.)

The determination of the pressure on the cutting edge can be found as follows:

Resultant pressure $R = A \times K$, where A = Area of cut
K = Constant.

For a depth of cut of $\frac{1}{10}$ in. (0·1 in.) and a feed of $\frac{1}{16}$ in. for a H.S.S. tool operating on mild steel, the constant K is taken as 120.

$$\therefore R = A \times K$$
$$= D \times F \times K$$
$$= \tfrac{1}{10} \times \tfrac{1}{16} \times 120$$
$$= \tfrac{120}{160} = \tfrac{12}{16} = \tfrac{3}{4} \text{ ton}$$
$$R = \mathbf{0{\cdot}75\ tons = 1{,}680\ lb.}$$

It is obvious that this load $\frac{3}{4}$ ton, on such a small area gives a high figure, and this fact, as mentioned elsewhere, limits the cutting speed and incidentally the tool life.

Values for K, i.e. the pressure in tons per square inch on the cutting edge as determined from tests, are approximately as follows: aluminium, 40–50; cast iron, 80–90; soft steel, 100–110; medium steel, 120–130; hard steel, 135–150. These figures are good averages, and can be used

TABLE 9

Area of Cut A Sq. in.	*Cast Iron Medium Ft./Min.*	*Mild Steel Ft./Min.*	*Steel 30–40 Tons Ft./Min.*	*Steel 50–60 Tons Ft./Min.*
0·001	60	130	100	75–80
0·002	50	120	85	65
0·003	50	110	75	60
0·004	45	90	65	55
0·005	45	85	60	50
0·006	45	80	55	45
0·008	40	75	50	35–40
0·015	35	65	45	30–35

in trial calculations for areas of cut from which depths and feeds may be obtained. When cutting pressures are high, it is obvious that they will accelerate tool wear, and cutting speeds should be fixed accordingly.

Table 9 gives representative cutting speeds for given values of area of cut A for various materials

The tangential force just referred to is really the single force which is the resultant of three component forces, namely, the main cutting pres-

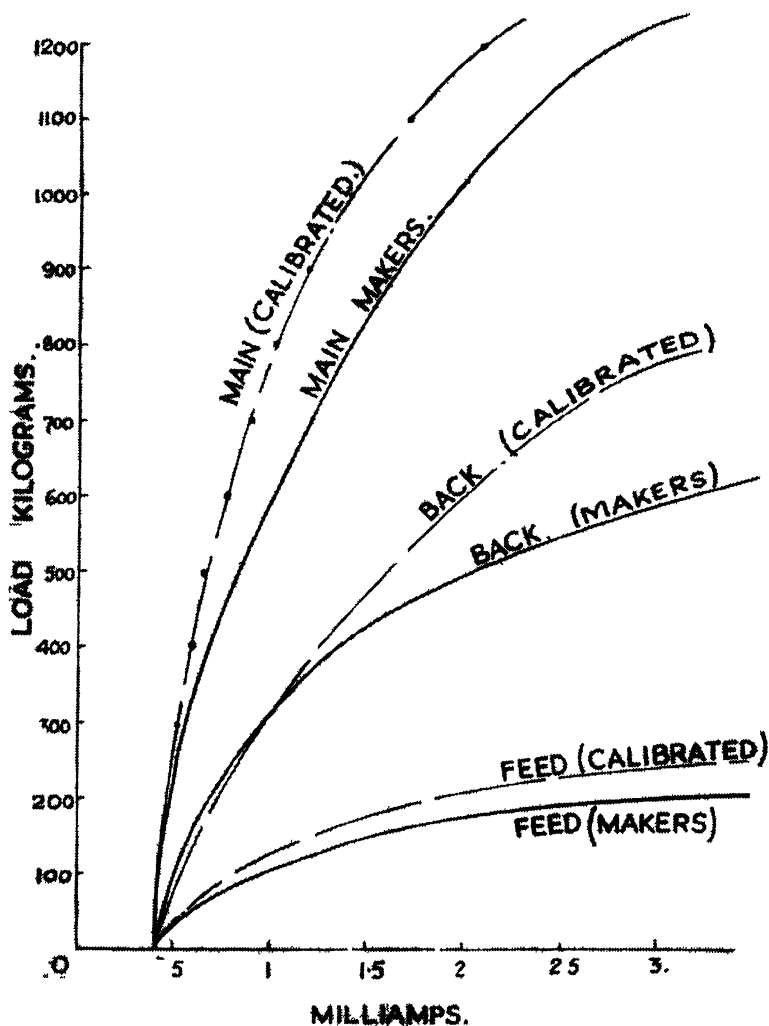



FIG 20

sure, the back pressure, and the feed pressure. These three forces act, as their names imply, in a downward, transverse, and longitudinal direction in relation to the workpiece, and are shown diagrammatically in Fig. 22.

The resultant force is shown which corresponds to the tangential force as calculated from the power used during the operation.

The determination of the individual pressures is possible by means of an instrument known as the Lathe Tool Dynamometer manufactured by Messrs. Schiess Defries A.G., Dusseldorf.

The apparatus works on the principle of an electrical system which transfers the tool pressures to diaphragms situated in a field circuit. The pressure on the tool deflects the diaphragm, which reduces the distance between the diaphragm plate and a solenoid, and in so doing varies the field strength. This variation is recorded in milliamps on three wattmeters or milliammeters, one for each of the three cutting pressures, main, back, and feed.

Fig. 20 shows the curves for this instrument, giving the values from the maker's original figures and a curve from values obtained by calibration of the instrument. It will be seen that with the aid of this chart the meter readings can be converted into loads in kilogrammes and further converted into pounds if desired.

A sketch of the equipment is shown in Fig. 21.

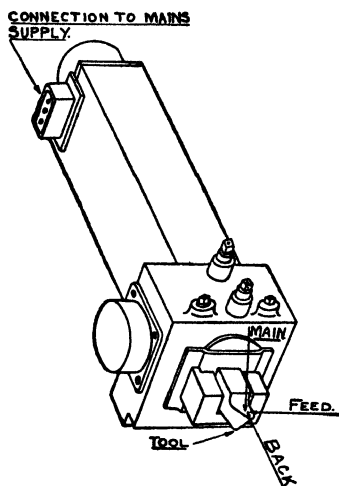



FIG. 21

The forces just mentioned are shown graphically in Fig. 22, in which the main force M, feed force F, and the back force B are indicated in a typical lathe cutting operation. To obtain the resultant of these forces, it is usual to combine first the main and back forces M and F and find their resultant R_{MF} by the application of Pythagorus's Theorem :

$$R_{MF} = \sqrt{M^2 + F^2}$$

Having determined this resultant either graphically or as above, the combination of the back force B and the newly found resultant R_{MF} can be accomplished, and thus the resultant of the three constituent forces determined :

$$R^2 = R_{MF}^2 + B^2 \quad \text{and } R_{MF}^2 = M^2 + F^2$$
$$R^2 = (M^2 + F^2) + B^2$$

The first step, finding the resultant, also involves finding its position :

$$\tan a = \frac{\text{Feed force}}{\text{Main force}} = \frac{F}{M}$$

= Angle at which the resultant of F and M acts to the vertical (see Fig. 22).

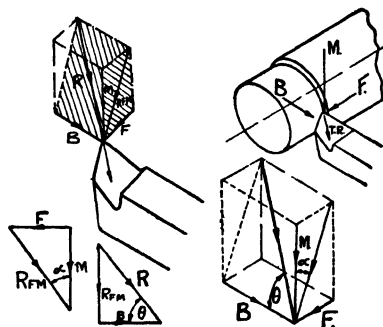
The second step, to find the resultant, is completed by finding the angle θ at which the force R acts:

$$\tan \theta = \frac{R_{MF}}{B}$$

Cutting Tools

To fully appreciate the lathe tool and its work, it is necessary to consider how the metal is actually removed during cutting. The metal is torn rather than cut, and in point of fact is sheared along a line, known as the shear plane, which is situated approximately at 90° to the tool-top face. This shear plane is shown in Fig. 15B.

FIG. 22—CUTTING FORCES

The metal is sheared along this plane by a force acting in the line of shear, and at cutting speeds the metal is removed in the form of a continuous chip. The chip itself, in the proximity of the parent metal, is preceded by a small crack, known as the "Taylor Crack," which runs ahead of the tool point. This crack is caused by the tearing action, and the full force of the chip on the tool is located at point P, the pressure point.

The force of the work on the tool can be resolved along the line of shear to give the shearing force, and the disposition of the forces is as shown in Figs. 22, 69, and 69A.

The cutting tool itself must possess a number of properties which can be defined as follows:

1. *Hot hardness* or *red hardness*, which is the ability to retain a cutting edge at high temperatures.
2. Strength.
3. Resistance to shock.
4. Resistance to abrasion.
5. Not subject to built-up edge.
6. Low coefficient of friction.
7. Give good surface finish.
8. Cheapness, i.e. low initial cost.
9. Weld ability.
10. Available in standard sizes and sections.

The majority of the above items need no elaboration here; but items 1 and 5 might be emphasised. Red hardness, the property of resisting

the softening effects of high temperatures, is illustrated in the graphs shown in Figs. 23 and 24, which show the values of the Brinell hardness

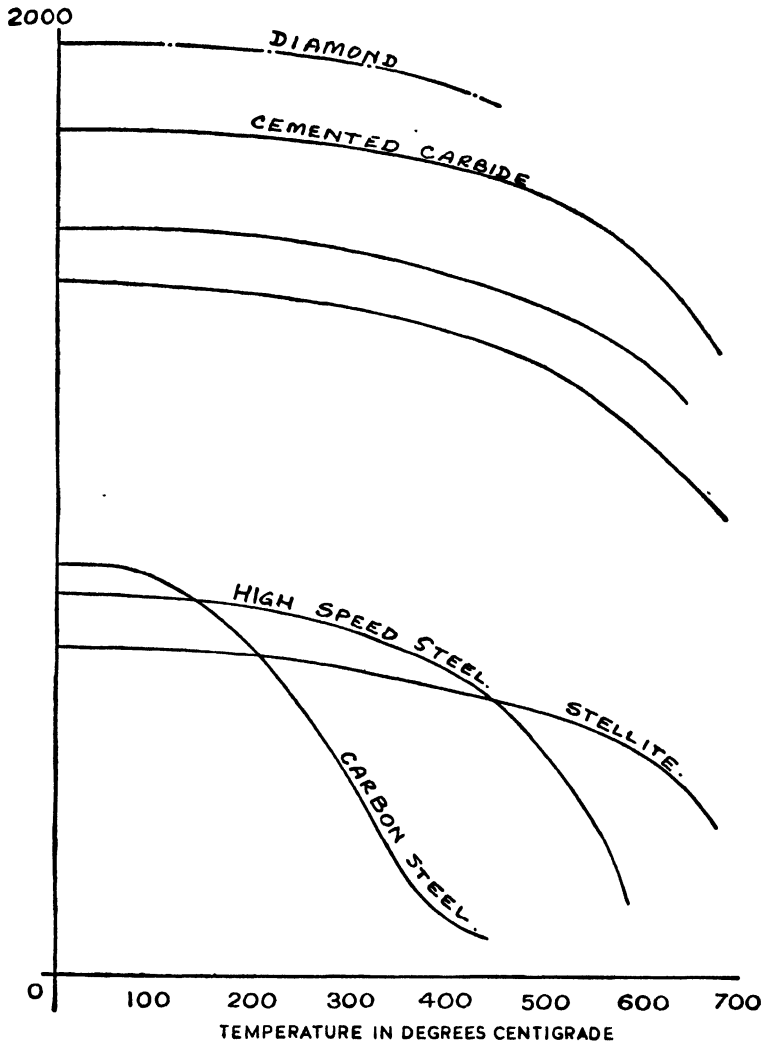



FIG. 23—BRINELL HARDNESS OF CUTTING TOOLS

number vertically plotted against temperature in degrees centigrade horizontally, and red hardness and toughness respectively in the same manner.

From these graphs it is readily seen that red hardness is obtained at the

expense of toughness, and the well-known cemented carbides, which have a high red hardness value, are in fact brittle. The manufacture of cemented carbides is now well established, and the quality of the tool tips constantly improving, but compared with materials of lower hardness, their toughness value is low. The cemented carbide for actual hardness is second to the diamond.

High-speed steels (H.S.S.) retain their hardness up to approximately 600° Centigrade.

Brief notes on cutting tool materials are given later.

Built-up Edge.—When a tool is cutting, the point where the lubricating effect of the coolant is most required is covered by the metal being

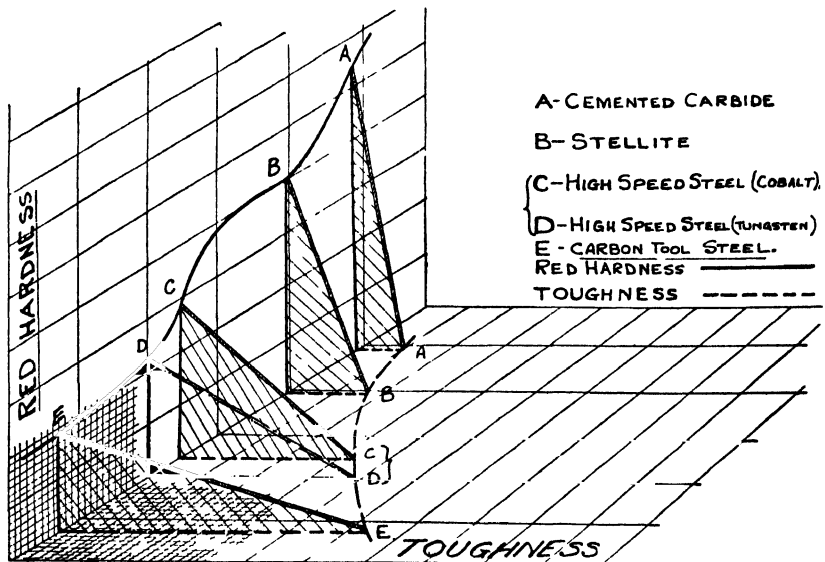



Fig. 24—Comparison of Red Hardness and Toughness

removed. Moreover, even if the oil or coolant were to reach the tool point and cutting edges, it is more than likely that the pressure of the chip and its flow over the tool-top face, and its portion of the heat generated during cutting, would soon force the coolant away from the vital spot. Therefore, a short time after the tool starts to cut, the edge and top face become clean and heated up, leaving a surface which is to all intents a chemically clean surface and in a condition to attract other metal, or, better still, it is in a position to build up by receiving other metal. This it proceeds to do, and as the particles of metal from the chips flowing over the tool-top face begin to build up on the edge and top face, the friction is increased. That is, the built-up edge offers more resistance to the chip flow and this in turn accelerates the growth of the built-up edge.

When the built-up edge has reached a height which renders the accumulated metal weak and unable to resist the flow of the chips passing over it, it breaks away, and the small pieces of this relatively hard metal are carried away in the underside of the chip and on the surface of the workpiece.

In the power consumption tests previously referred to, the tools developed built-up edges and the amount of edge appeared to increase as the rake angle increased, but no definite conclusion could be reached, since steps were not taken to investigate this. The built-up edge, however, was about $\frac{1}{8}$ in. high on the top face of the tool, which was of a high-speed steel. Usually a built-up edge indicates too slow cutting speed.

Cutting-tool Materials

Carbon Steel.—These steels are known as high-carbon steels and usually contain more than 1 per cent. of carbon (one per cent.), although it is found that steels with 0·8–1·4 per cent. carbon are used for cutting tools. The Brinell hardness number for these steels is in the region of 600–650 and on the Rockwell scale C 60 approximately. The tools are ideal for low cutting speeds and for tools such as complex form tools which do not require grinding, or are difficult to grind after hardening. The carbon-steel tool gives a good surface finish to the work, retains its cutting edge under normal conditions, is cheap, and easy to temper. It is hardened by heating to a temperature of 780–840° C., depending on carbon content, and then quenching in oil or water. It is tempered at 220° C., but has a poor red hardness figure, losing hardness if heated to approximately 300° C.

High-speed Steel (H.S.S.).—This is a steel containing a fair percentage of tungsten, usually about 18 per cent., although it may vary between 12 and 20 per cent. The carbon steel, usually 0·7–0·85 per cent. carbon plus 14 or 18 per cent. tungsten, makes a very hard tool with better red hardness properties than carbon tools. It is capable of being operated at higher speeds than carbon steel without any appreciable loss of hardness, and in fact keeps its hardness and cutting edge to temperatures of 610–620° C.

It is hardened by heating firstly to 800–850° C. at a slow rate, then it is transferred to another furnace and rapidly heated to 1,200–1,300° C. The temperature varies with the tungsten content and alloying elements, such as chromium, vanadium, carbon, etc. It is tempered at 580–610° C., this operation being in effect a secondary hardening process, as, unlike carbon steel where tempering reduces hardness but increases the toughness, tempering the H.S.S. tool consolidates the hardness, and within the range just mentioned, i e. 600° C. approximately, it is " self-hardening."

Stellite.—This is a non-ferrous alloy compounded of cobalt, chromium, and tungsten, and it possesses a greater cutting power than high-speed

steel. At 1,000° C. stellite has the same Brinell hardness as H.S.S., roughly 60–70, but up to 600° C. has a B.H.N. of approximately 500. It is non-magnetic, rustless or non-corrodible, and acid resisting, and has a low coefficient of friction.

In cutting performance it is between H.S.S. and the cemented carbides. It is used in the form of tips for tools, being brazed or welded to steel shanks, and for facings for tools, gauges, etc. Carbon is added to the composition in some cases, and the alloy is inherently hard and requires no heat treatment.

Cemented Carbides.—Tungsten carbide is the main constituent of this type of material, and it is obtained from tungsten ore, which is crushed and chemically treated to give a tungsten metal powder that is used in lamp filaments.

It is mixed with cobalt to form tips for tools. The correct grade of carbide tip should be used, as these are carefully designed by the makers for each specific job and material. For example, a tool tip designed for cast iron would be subject to a built-up edge if used for steel. The difference is shown by the composition of the material used for these two metals.

Cast Iron		*Steel*	
	Per cent.		*Per cent.*
Tungsten carbide	94	Tungsten carbide	76
Cobalt	6	Titanium	18
		Cobalt	6

The titanium acts as a lubricant within the material, and prevents breaking off. The cobalt prevents the brittleness associated with this material, and as its content is increased the material becomes softer and more tough.

Fine crystals of the tungsten powder (0·001 in.) are held in a matrix of cobalt which acts as a bond in much the same way as the bonds for grit in grinding wheels. The powder, covered with the coating of cobalt, is treated by two sintering operations, first the mixed powders are placed in a suitably shaped die and subjected to pressure which varies between 15 and 1,500 tons per square inch according to size and capacity of the dies, and this is followed by a presintering operation at approximately 900° C. At this stage the material can easily be machined, and any shapes, forms, or special characteristics are put on the carbide tip or tool. The final operation is the sintering at 1,200–1,500° C. in an electric furnace in a reducing atmosphere.

The tips can be ground to give the required values of rake, clearance, form, etc., and the makers of the tips give recommendations for wheels suitable for the grinding of the metal. It is best to finish the tool with a metal-bonded diamond wheel or diamond lap to give a superfine cutting edge which gives good service and tool life.

Cemented carbide " craters " rather badly, but this condition can be offset by designing the tool so that the chip flow clears the tool, and incorporating a chip breaker groove, to break up the coiled or flowing continuous type of chip into small pieces. At the high cutting speeds rendered possible by the cemented carbide tool, the question of swarf removal is an important one. The hardness of the material is second only to the diamond, giving values of 1,850–1,900 B.H.N.

Diamond.—The diamond is a natural cutting stone, and for hardness comparisons the value of 2,000 is given and indicates the relative hardness between itself and the other cutting-tool materials. It is used mostly for turning operations on non-ferrous materials, as so far it has not been very successful in cutting steels. It is capable of giving a high surface finish up to 1 or 2 micro-inches, and can be operated at high speeds. In fact, for turning the diamond can only be successfully used for finishing. The difference in performance between the diamond and the cemented carbide is almost as much as the difference between cemented carbides and high-speed steel.

The cutting speed for a diamond should be as high as possible, the lowest value for economical use being about 250–300 ft. per minute. High speeds of the order approximating to 10,000 ft. per minute have been used when operating on non-ferrous material, such as copper and aluminium alloys, but a good general figure for cutting speed would appear to be in the region of 1,200–1,500 ft. per minute, although this value is dependent on the feeds used.

For aluminium-alloy pistons for internal-combustion engine work, cutting speeds between 1,500 and 2,000 ft. per minute have been attained, the feed being between " half a thou " (0·0005 in.) and two thousandths of an inch (0·002 in.).

The depth of cut permitted by this cutting tool is not great, and successful figures for this quantity lie between 0·006 in. and 0·026 in.

The fine feeds and relatively high speeds used produce a surface free from spirals or tool marks, and diamond toolholders which have been set in an adapter, producing in effect an inserted diamond tooth milling cutter, have been used for milling, with the result that highly polished flat surfaces have been produced.

From the tenor of the remarks just made it is obvious that if there is any amount of metal to be removed, the majority should be turned off by other tools before finishing with a diamond. The same applies to cast materials with an uneven surface or " skin " on them which would seriously affect the performance of the diamond tool.

The values of the clearance angles and top-rake angles are given in the following table, and these will be found to be good average figures for H.S.S. tools

TABLE 10

Material	*True Top Rake, degrees*	*Clearance, degrees*
Mild steel 25–32 tons/in.^{2} tensile	20	6
Steel 35–42 tons/in.^{2} tensile .	15	6
Steel above 50 tons/in.^{2} tensile	10	4
Steel (as Cast) . . .	15	6
Cast iron	10	8
Chilled, C.I.	0–4	4
Copper	12	10
Brass	0–6	10
Phosphor-bronze . . .	6	10
Aluminium	30–40	10
Duralumin	40–50	10
Wrought iron . . .	10–15	6–10

As will be seen from the table, the clearance angle is generally between 6° and 10° for external turning.

For internal work, i.e. boring, the clearance is often determined by the work, and must be sufficient to allow the tool to clear the work. In some cases the clearance usually applied can be ground on the boring tool, and then a secondary clearance is added in order to allow the tool to clear the work.

Exercises on Chapter II

1. A drill is required to drill holes from $\frac{1}{16}$ in. diameter to $\frac{1}{2}$ in. diameter. Calculate the range of speeds for six speeds arranged in geometric progression, and give the corresponding drill sizes for which each speed is suitable. Cutting speed S is 90 ft. per minute.

2. What would the speeds be in Question 1 if the drill was reserved for work on aluminium at a cutting speed of 250 ft. per minute ?

3. Plot the speeds found in Question 1 and draw the straight line between the first and last speeds, and from it read off the corresponding speeds in arithmetical progression.

4. If the relationship between cutting speed S and tool life T is $ST^{\frac{1}{8}} = C$, find the probable tool life for a H.S.S. tool operating on mild steel if S is 100 ft. per minute giving the expression the value $ST^{\frac{1}{8}} = 200$.

5. For cutting steel with a carbide-tipped tool the value of n in $ST^n = C$ is $\frac{1}{5}$. Calculate the cutting speed S for a tool life of $2\frac{1}{2}$ hours between regrinds if $ST^{\frac{1}{5}} = 320$.

6. A mild-steel bar 4 in. diameter is being turned at 110 ft. per minute with a depth of cut 0·125 and a feed of 0·01 in. If the power consumption when cutting is 1·9 kW and when running light is 0·4 kW, find (*a*) the tangential force, and (*b*) nominal pressure on the tool point.

7. If the same bar as in Question 6 is being turned at 140 ft. per minute with a feed of 0·01 in. and cut consumes 1·65 kW, and 0·35 when running light, find the depth of cut permissible if the nominal pressure on the tool is limited to 100 tons per square inch, and also find the tangential force.

8. If in Question 7 the depth of cut were reduced to 0·125 in., what value of cutting speed could be used, all other items being as given in previous question ?

9. A cutting tool has a front clearance angle of 8° and top rake of 20°. If it is set $\frac{1}{8}$ in. above centre, what are the new rake and clearance angles? Diameter of bar is 3 in.

10. What would be the values of rake and clearance angles in Question 9 if the tool were set $\frac{1}{8}$ in. below the centre line of work, which is 3 in. diameter in each case?

11. (*a*) At what height above the centre will the tool rub? (*b*) At what point will the rake angle be reduced to zero in the above question?

12. Describe the properties of a good cutting-tool material.

13. What do you understand by the term "Red Hardness"? How does this property compare with toughness? Sketch the two quantities in relation to each other for the common cutting-tool materials.

CHAPTER III

CAPSTAN AND TURRET LATHES

A CAPSTAN lathe differs from an ordinary lathe in that, instead of the usual tailstock, it has a turret with six stations in which tools for various operations can be placed and brought up to the work.

The turret of a capstan lathe—on the smaller sizes it is usually circular and generally for the majority of capstans is hexagonal—moves on a capstan slide or rest, which is not part of the lathe bed but separate. The hexagonal turret or capstan revolves, bringing in turn the tools it carries into line with the work spindle. They can then be fed either by hand or by an automatic feed into the work, and the operation is generally much quicker than on an ordinary centre lathe. In addition, the front cross slide is also capable of being set to stations, so that when the machine is

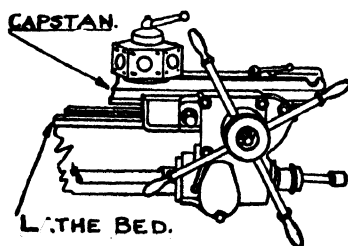
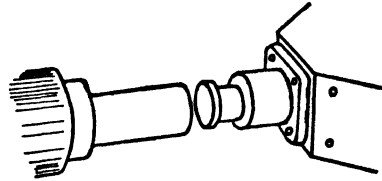



FIG. 25—CAPSTAN

set up for a given workpiece the part can be made and repeated by feeding the bar stock through the collet in the spindle nose. Fig. 25 shows a typical capstan turret mounted on its slide or rest. The attachment of the tools to the turret may be either by a square or rectangular flange or by a circular shank, and these tools perform a number of varied operations, such as centring, turning, drilling, tapping, threading, chamfering, reaming, and boring. These operations, and those usually performed from the turret, will be discussed in the following order.

Bar Stop.—This can be either a simple stop, set so that when the turret is brought up, it limits the amount of bar stock fed forward, to the length required for the job in hand (the setting of the capstan stops to obtain the correct travel of the capstan turret will be discussed later), or a combined bar stop and centre drill. In both cases the stop is brought up into position and the bar allowed to come forward under the influence

of the bar-feed mechanism, thus ensuring that the same length of material is fed forward for every component. Fig. 26 shows a standard bar stop and also a combined bar stop and centre drill. There are several types of this latter, one as shown, and one in which the stop for locating the bar length is mounted on a pivot and can be swung into position over the centre drill and removed when the bar has been fed through, allowing the drill to be brought forward by means of a small hand lever.

COMBINED BAR STOP AND CENTRE DRILL.

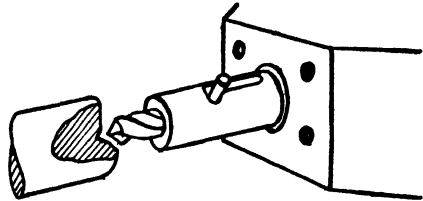



FIG. 26

Once the bar has been centred, drilling can proceed, but it should be remembered that the ends should be faced square before centring and drilling where this proves necessary.

The drilling operation is a straightforward one, and is as shown in Fig. 26A.

If the hole requires reaming, the operation is similar to drilling, and is

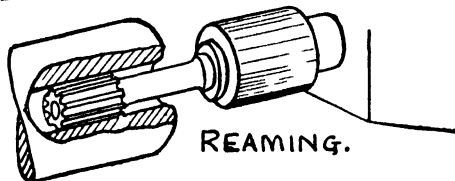
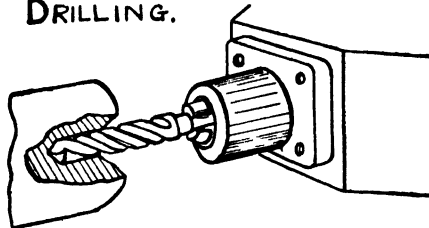



FIG. 26A

accomplished by following the drill by the reamer, usually at slower speed but at a greater feed. The set-up for a reaming operation is shown in Fig. 26A above.

If the drilling is to be followed by a tapping operation, a tap is fed

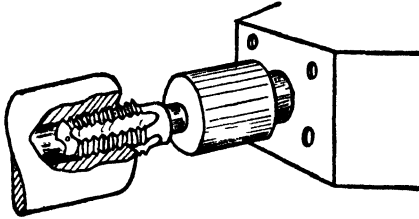
forward in the same manner as the drills and reamers, but in this case the tap must be of the collapsible type or the spindle rotation reversed in order that the tap may be extracted.

TAPPING

FIG. 27

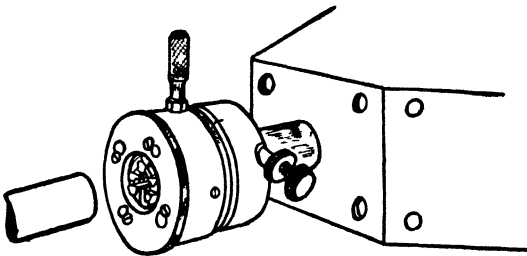
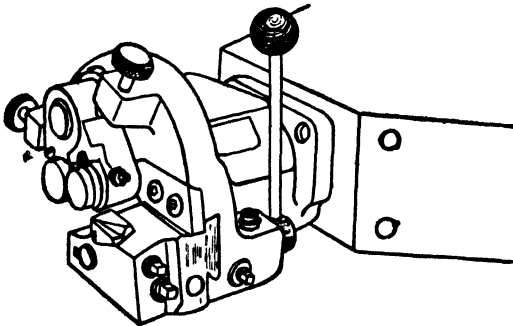
For external threads a self-opening diehead is used, and this does not need a spindle reverse, but it is necessary to reduce the spindle r.p.m. before cutting the thread. The arrangement of the diehead for screw cutting is shown in Fig. 28.

THREADING (DIEHEAD.)

FIG 28

Much of the turning done on capstan lathes is performed from the turret by roller-box turning tools, which, as the name implies, are tools of box shape with support rollers fitted which hold the work and support it during cutting.

The front cross slide carries a square tool post, shown in Fig. 30, and the operations done by tools mounted in this unit are turning, facing, chamfering, undercutting, and forming. Parting off is also a front cross-slide operation, but it may be equally well achieved from the rear cross slide by inverting

ROLLER BOX.

FIG. 29

the parting-off tool. A fair indication of the disposition and layout of the turret and cross-slide tools has already been given in the examples in Chapter I, and it will only be necessary to supplement this by an indication of a typical square tool post for representative operations of forming, chamfering, and parting off, which is depicted in Fig. 30.

Capstan Mechanism

The main function is that of the turret indexing. This is performed as follows: Referring to Fig. 31, which shows the parts concerned, the

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FIG. 30—SQUARE TOOL POST

hexagon turret can be seen on the capstan slide from which it has been removed, and the index ring K, ratchet M, and bevel wheel O are clearly visible. This illustration indicates the method of dismantling the turret, which is accomplished by rotating locking lever A in an anti-clockwise direction. The cap B, washer C, keywayed ring D and two locking pins E can then be removed. The hexagon turret is then free except for index bolt F, and this can be removed by carefully and slowly rotating the star wheel which is fitted to splined shaft G until disengagement takes place, at which point the index bolt F is withdrawn from the slot L in ring K. Care should be taken to see that finger F does not withdraw too far and recede under cover H, which would then present difficulty in bringing it forward again.

Referring now to Fig. 32, this shows the capstan rest and hexagon turret of a *Ward* Capstan Lathe, in which the hexagon capstan G is re-

volved automatically on the return or backward stroke of the slide. This is effected as follows:

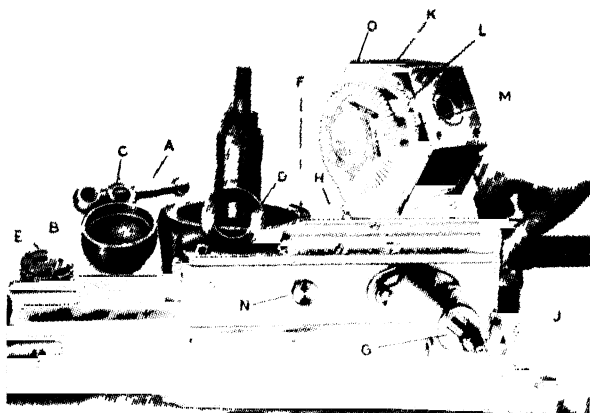
As the slide moves backward, the withdraw finger *H* catches an incline *J* on the rest. This incline temporarily keeps the lower part of the withdraw finger from moving endwise, but it is pivoted in the top slide, and as it swivels, the top part of it withdraws the index bolt *F* (Fig. 31) from index ring *K*. After the bolt has been withdrawn, a further backward movement of the slide causes the rotating finger *K* (Fig. 32) to strike the ratchet *M* and so push the capstan round one-sixth of a revolution. Just

Courtesy Ward Ltd., Birmingham.

FIG. 31—CAPSTAN MECHANISM

before the capstan reaches this position, the withdraw finger passes completely over the incline and allows the index bolt to return in time to locate itself in the next slot in the index ring.

By referring jointly to Figs. 31 and 32, it will be seen that between the index ring *K* and ratchet *M* (Fig. 31) a bevel wheel *O* is placed. Meshing with this bevel wheel is a pinion *L* (Fig. 32) which is fixed to stoprod *M*, and this stoprod is in turn fastened to the stop barrel *N*. This barrel *N* carries six stops *O*, and as the ratio of these bevels is 5 : 1, it will be readily understood that for every sixth of a revolution of the capstan the stop barrel makes five-sixths of a revolution and so brings a fresh stop to the stopface. The stops are screwed, and long enough to be adjusted to control operations on any piece of work within the range of the capstan slide, and each stop has a locknut *P* to prevent them moving when once they have been set.

In capstan lathes the capstan rest is perhaps the most important unit, because on it depends to a great extent the accuracy of the work produced by the machine.

The capstan slide is fitted to a suitable base, this base being arranged

so that it can be secured to the lathe bed in the required working position.

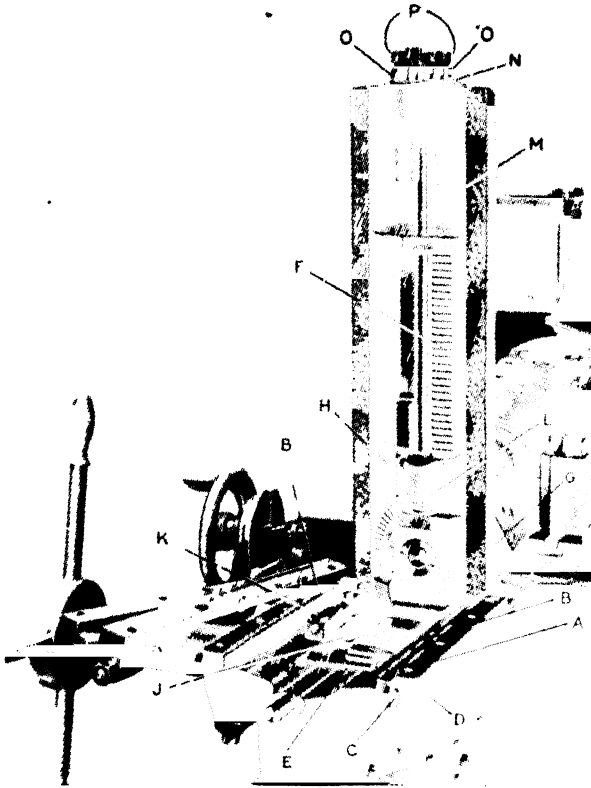
The base *A* in Fig. 32 is provided with two taper strips *B* which can be adjusted to take up any wear that may develop. In each taper strip is a slot in which the head of an adjusting screw *C* fits. By turning the

Courtesy Ward Ltd., Birmingham.

FIG. 32—CAPSTAN MECHANISM

screw, the taper strip is moved in or slackened off as required. When the required adjustment is obtained, the adjusting screw is fixed by pressure from a small gunmetal pad which is controlled by the small screw *D*; thus the taper strip becomes immovable. This is shown in Fig. 33.

As indicated at the beginning of the chapter, the smaller sizes of capstan lathes have circular turrets, and usually take bar work up to 1 in. diameter, the Ward No. 0 ungeared capstan taking ⅝ in. diameter maximum without wire feed and ½ in. diameter maximum with wire feed.

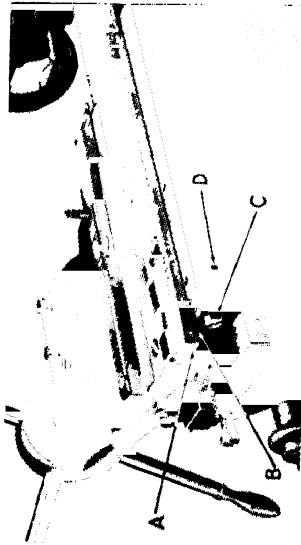
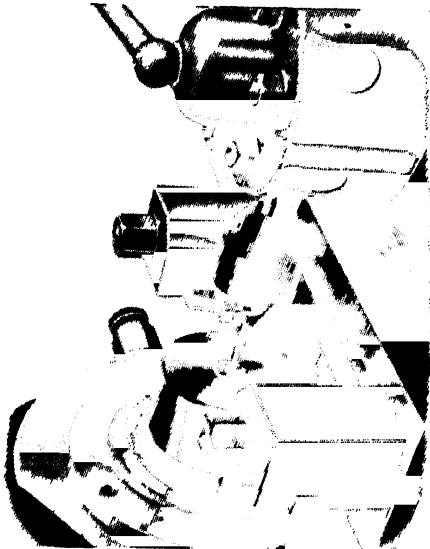
The following figure indicates the Ward No. 0E machine equipped with special tooling equipment for machining small gears made from pinion wire.

Courtesy Ward Ltd., Birmingham

FIG. 33

Courtesy Ward Ltd., Birmingham

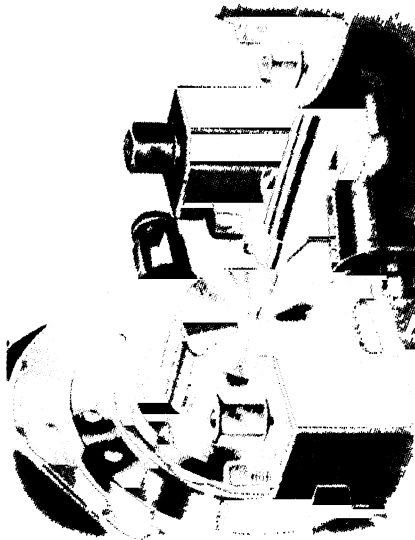



FIG. 34A

Courtesy Ward Ltd., Birmingham

FIG. 34

The larger sizes take up to 2⅝-in. diameter bar, and in addition the capstan lathe can be used for chucking, in which case the diameter of the work handled is very much larger than the bar work handled by the same machine.

The Ward No. 2A Capstan is shown in the following figures tooled up for various operations.

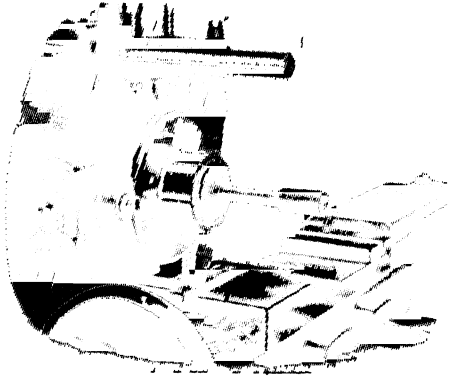



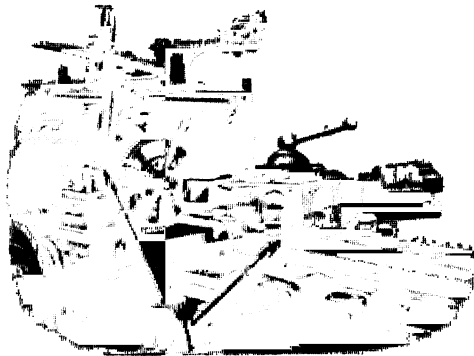
FIG. 35

Courtesy Ward Ltd, Birmingham.

FIG. 36

Fig. 35 shows an aero-engine valve.

Fig. 36 shows the second machining process on a water mixer part, the tools in the turret being two special turning heads and a landmatic diehead.

Fig. 37 shows the No. 2A Capstan fitted with a jaw chuck and tools for machining a gear bracket.

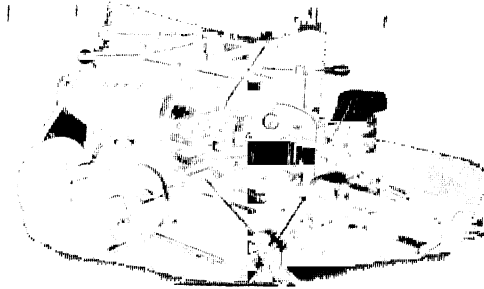
A notable capstan lathe is the Herbert No. 4 Senior. This has a pre-optive headstock, which is explained in Chapter VI.

Courtesy Ward Ltd, Birmingham

FIG. 37

The machine is shown in the following figures, Fig. 38 showing a front view of the lathe and Fig. 39 the rear view from which the compact

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FIG. 38—" HERBERT " NO. 4 SENIOR CAPSTAN LATHE WITH PREOPTIVE HEADSTOCK

motor drive and pipelines for internal supply of cutting lubricant to the capstan are clearly seen.

The preoptive headstock enables speed changes to be made while the tools are actually cutting, and the tools need not be withdrawn, a great advantage when carbide tools are being used.

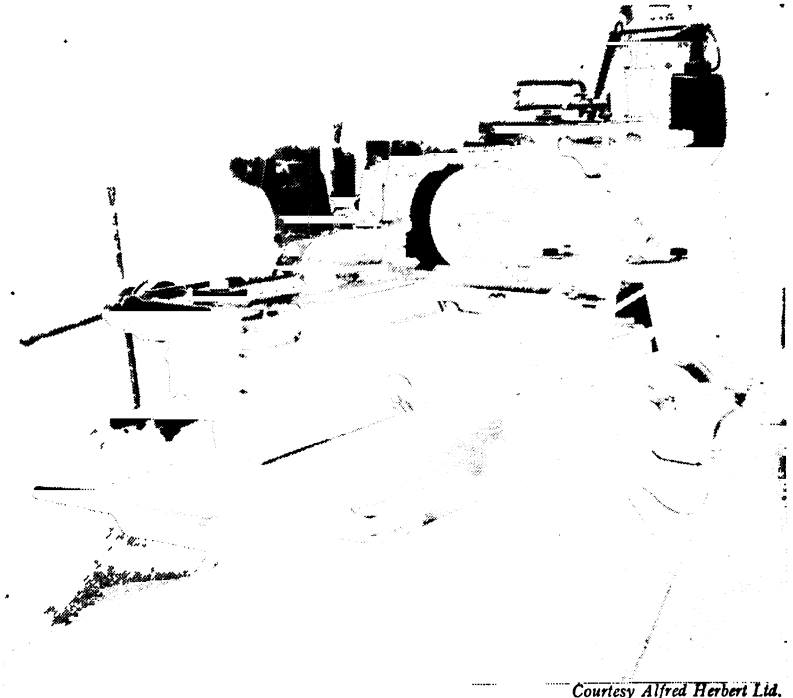
The ease of operation and simplicity of the electrical controls of this machine are indicated in the following diagrams.

Courtesy Alfred Herbert Ltd.

FIG. 39—REAR VIEW NO. 4 HERBERT SENIOR LATHE

In Fig. 40 the preoptive motor and electric pump motor push-button controls are seen below the feedbox.

The spindle can be started, stopped, reversed, or inched round by means of control push-buttons on the front of the headstock. These push-button controls are shown in Fig. 41 in which the spindle is being started up for forward motion.

The spindle speeds are preselected by means of a dial, as indicated in Fig. 42. When the change in speed is required, the knob in the centre of the dial is depressed and the change in speed is made while the tools are cutting.

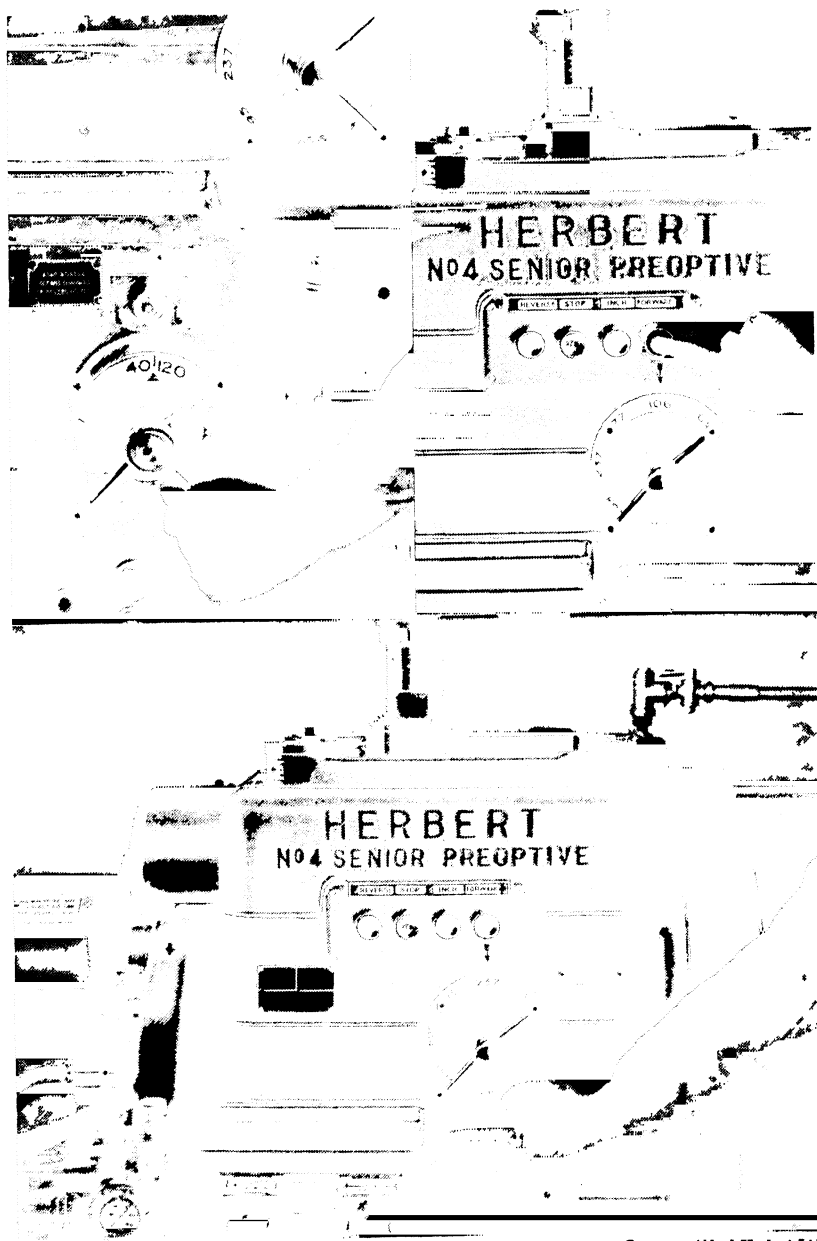
The operation of the mechanism is further explained in Chapter VI.

Courtesy Alfred Herbert Ltd

FIG. 40—Top left SELECTING FEEDS FIG 41—Top right STARTING SPINDLE. FIG 42—Lower SELECTING SPEEDS

This particular capstan is suitable for negative-rake cutting, and is fitted with a 7½-h.p. motor ; standard speeds are 42–1,000 r.p.m., with two-speed motor 20–1,000 r.p.m., the automatic feed range is 40–480 cuts per inch, and the general disposition of this latter is shown in Fig. 40. The feedbox provides six automatic feeds between the figures of 40 and 480 cuts per inch to both saddle and capstan slide and three ratios of chasing feeds.

A general view of the headstock is shown in Fig. 43. In this instance

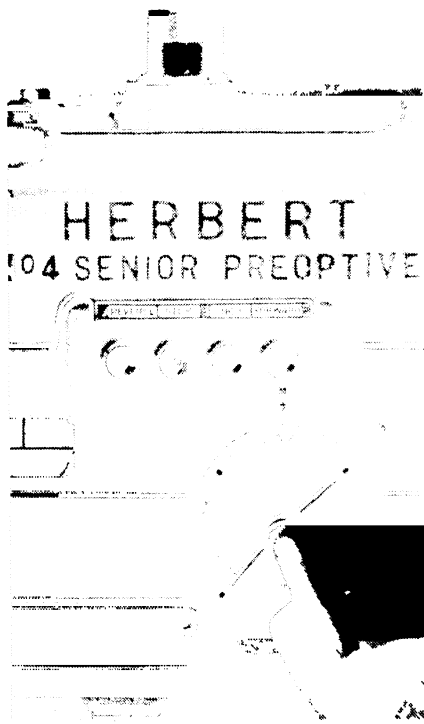



FIG. 43—METHOD OF CHANGING SPEED

in the machine we are considering the headstock is fitted with a two-speed motor and a dead-length bar chuck. This dead-length bar chuck can be either hand or air operated, and a view of the air-operated type is shown in Fig. 44.

This unit is incorporated in the headstock as shown, and its great advantage is that the collet or conical holders are stationary when the chuck is operated, so that there is no end movement of the work, and therefore work can be accurately located endwise.

The closing mechanism is internal, and no chuck tube being required, the capacity of the spindle bore is not therefore reduced.

For the accurate duplication of length dimensions on successive components, the movements of the slides carrying the tools are provided with accurate indicators which are combined with a graduated scale as shown in Fig. 45. These indicators and combined graduated scales afford easy and accurate settings, and facilitate the machining operations.

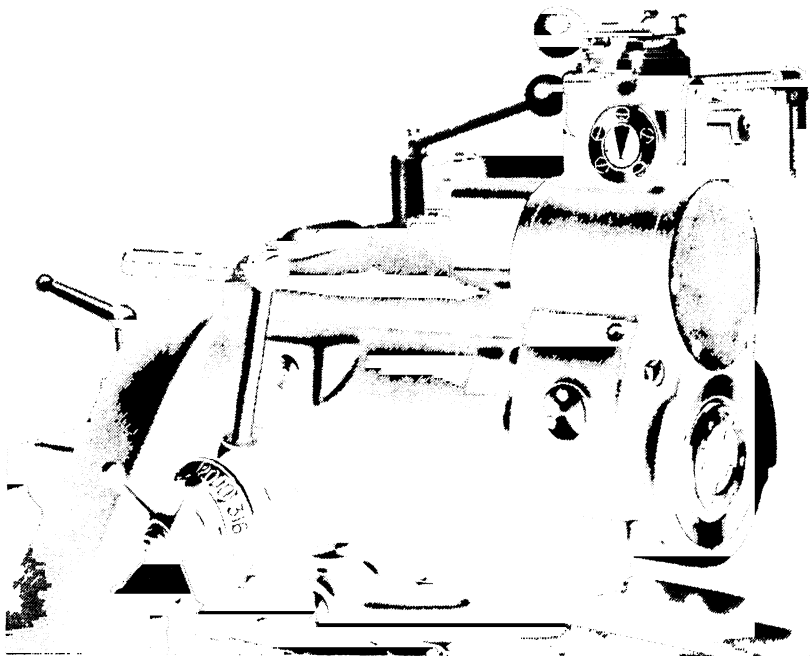
The square tool post can be seen in Figs. 30, 46 and 47. This tool post is quick acting and self-indexing, and can be used for a great variety of tool arrangements. The cross-slide tools are carried in this tool post or

Courtesy Alfred Herbert Ltd

FIG. 44—DEAD-LENGTH BAR CHUCK

square turret. Normally, four tools are accommodated, and these should be arranged so that each tool, when in the cutting position, is on the left of the square turret. This ensures that all operations on the work are carried out near the chuck. In addition to the usual type of tool used in the square turret for operations usually performed from the cross slide, in the case of capstan lathes former plates can be placed on the turret and a profiling slide arranged in the square turret. Or conversely a profiling slide may be attached to the turret and a former plate on the square turret.

As can be seen from Figs. 46 and 47, the saddle which carries the cross

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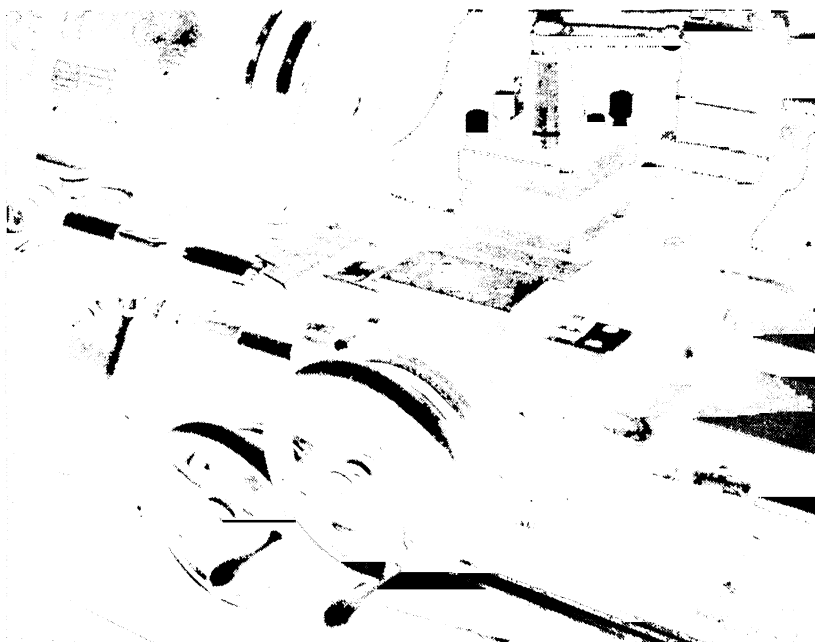
FIG. 45—ACCURATE INDICATORS

Courtesy Alfred Herbert Ltd

FIG 46—THE SADDLE

slide and square tool post just mentioned is provided with automatic sliding and surfacing motions. These motions are controlled by trips and dead stops.

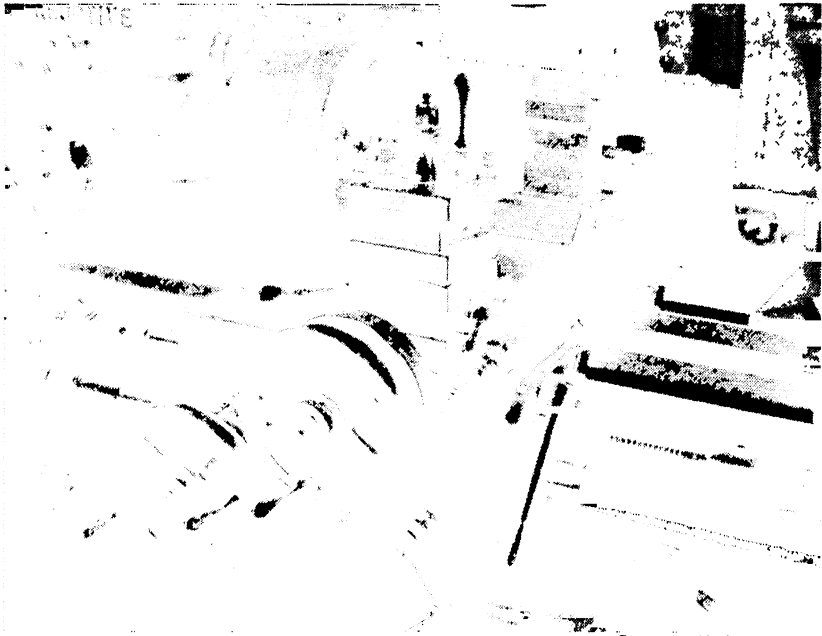
Fig. 47 shows the chasing saddle, and the chasing lever can clearly be seen at the right-hand side of the saddle. The chasing saddle is not standard equipment, but is supplied if ordered with the machine, and it is capable of chasing threads up to 9 in. long. Also in this view the quick-acting square turret can be seen. This is very rapid in operation ;

Courtesy Alfred Herbert Ltd

FIG. 47—CHASING SADDLE

one movement of the lever releases the clamp, and a reverse motion indexes and reclamps the turret.

The wearing surfaces of the " Herbert " lathes, such as the bed ways, capstan-slide mating surfaces, and the mating surfaces of the capstan block, are hardened by the firm's patent " Flamard " process. The parts concerned are shown in Fig. 48, which clearly shows the vee and rectangular ways, further details of which will be found in Chapter VI.

Further reference to Fig. 48 will reveal the hexagon turret and the toolholders fixed in position on two of the turret faces.

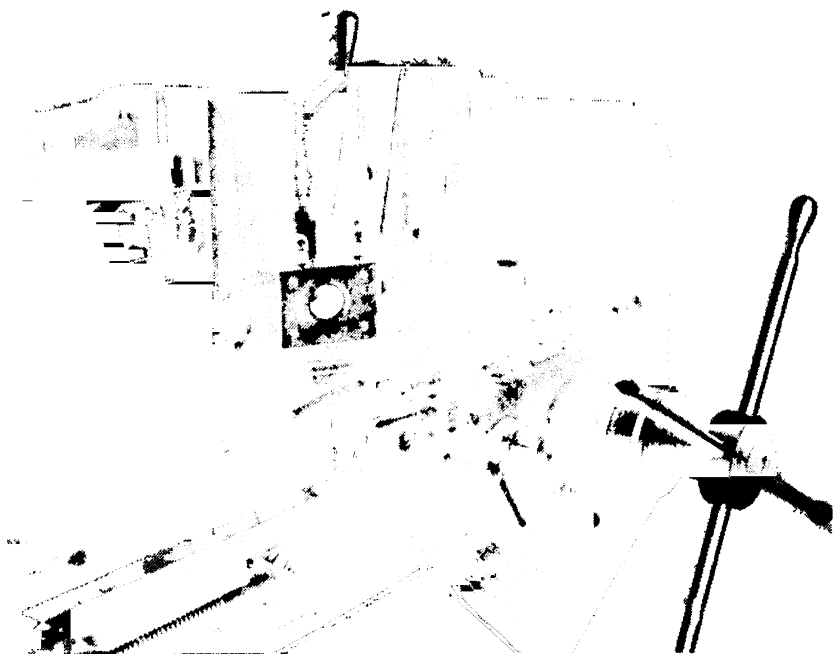
A general view of this lathe is given in Fig. 49.

Courtesy Alfred Herbert Ltd

Fig 48—Capstan Block, Slides, Bed Ways and Star Wheel

Courtesy Alfred Herbert Ltd

Fig 49—General View of Herbert ' No 4 Senior Preoptive Lathe

Turret Lathes

A turret lathe is similar to a capstan lathe in some respects in that it has a hexagonal turret which can be indexed round, bringing the tools it carries into line with the spindle and work. As distinct from the capstan, a turret lathe does not have a separate slide, the capstan or turret being carried on the lathe bed without the additional provision made in the capstan lathe.

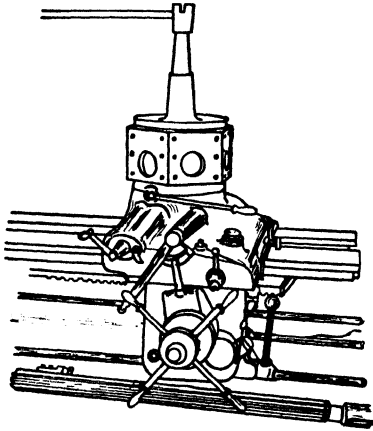



FIG. 50—TURRET IN TURRET LATHE

Speaking generally, the turret lathe is a heavier machine than the capstan, and usually caters for larger and heavier work.

In Fig. 50is shown the arrangement of the turret for this class of lathe. By contrasting this with the sketch of the capstan (Fig. 25), the difference between these two types of machine will be apparent.

Apart from the fact that the tools are generally heavier, their layout and operations are the same as those given for the capstan lathe. The turret is generally provided with " knee tool holders," which in themselves are capable of carrying a number of tools, thus increasing the usefulness of this machine.

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FIG. 51—" HERBERT " COMBINATION TURRET LATHE

In addition, combination tool holders increase the productivity of the lathe to which they are attached.

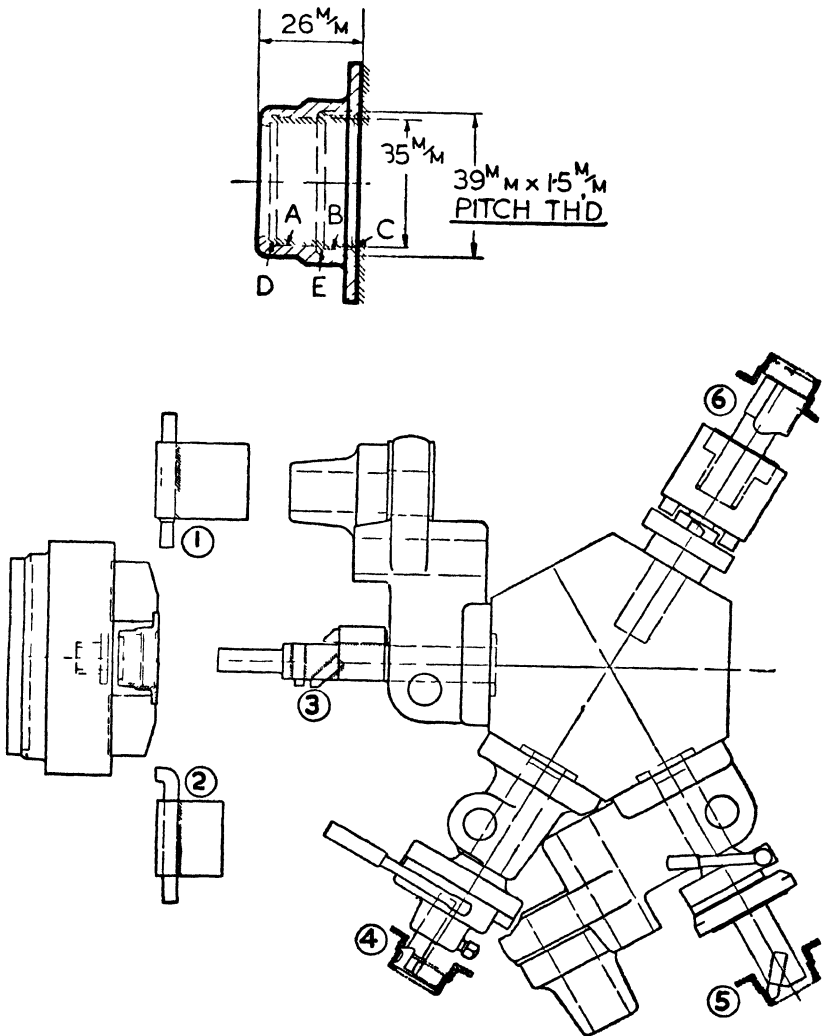
A general view of a turret lathe is given in the photograph reproduced in Fig. 51, which shows a "Herbert" Combination Turret Lathe. It will be clearly seen that the tailstock of the ordinary type centre lathe has been replaced by a hexagon turret, on which are mounted various attachments

Courtesy Alfred Herbert Ltd.

Fig. 52—Tool Layout

This turret slides directly on the lathe bed, as can be seen, and not on an independent slide, as does the hexagon turret of the capstan lathe.

Indication has already been given that the capstan and turret lathes are similar in their construction and operation, and the essential points of difference already discussed.

Also the question of tooling and of operation layouts for capstan lathes have been considered in Chapter I.

A further typical layout is given in Fig. 52, which shows a ball-bearing part and the disposition of the hexagon turret and cross-slide tools for the following operations. The material from which the component is made is duralumin, cut off from bar stock and held in soft jaws in the chuck.

Courtesy Alfred Herbert Ltd.

FIG. 53—PHOTOGRAPH SHOWING TOOLING FOR COMPONENT SHOWN IN FIG. 52

Operations

1. Rough face end with tool in rear tool post.
2. Finish face end with tool in front tool post.
3. Bore diameters *A* and *B* and chamfer at *C* with tools in boring bar held in hexagon turret.
4. Recess diameters *D* and *E*, using double recessing cutter in recessing slide in turret.
5. Size bore diameter *A*, using fine adjustment boring tool.
6. Tap bore *B*, using tap and dieholder.

A photograph of the above tooling showing the part being machined

is shown in Fig. 53, and from this view the various tools in the hexagon turret and cross slides can be seen.

A typical job and a tool layout on the " Herbert " No. 12 Combination Turret Lathe is the cylinder liner shown in Fig. 54.

The material from which the liners are made is cast iron, and as will

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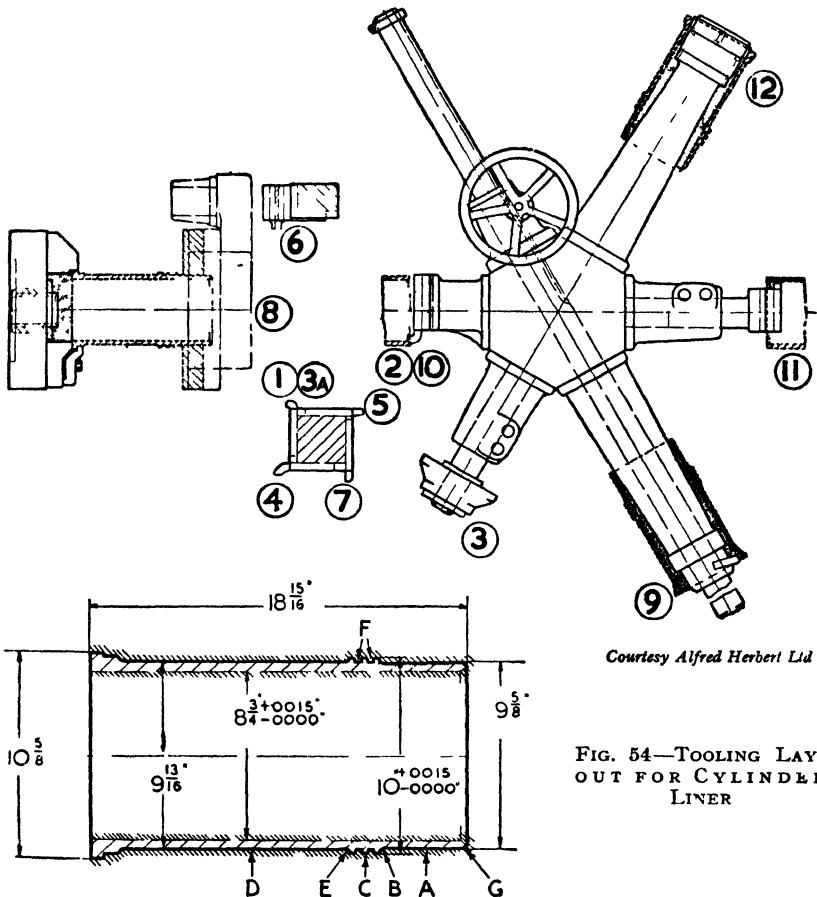


FIG. 54—TOOLING LAYOUT FOR CYLINDER LINER

be seen from the component drawing, the finished length of the iron castings is $18\frac{15}{16}$ in., and the largest finished diameter is $10\frac{5}{8}$ in.

The third operation list on these components is as follows:

1. Finish face end, using tool No. 1 in square turret.

2. Cone end of bore, using tool in special holder on first face of turret. Allowance left for finishing.

3. Support in coned mouth of bore, using revolving cone support in boring bar holder on second face of hexagon turret.

3A. Finish turn diameter A and face shoulder B, using turning and facing tool in square turret.

4. Finish turn diameter *C* and *D*, using turning tool in square turret.

5. Form $\frac{3}{16}$-in. radius *E*, using tool in square turret.

6. Finish form grooves *F* with tools in rear tool post.

7. Remove cone support and radius end *G*, using tool in square turret.

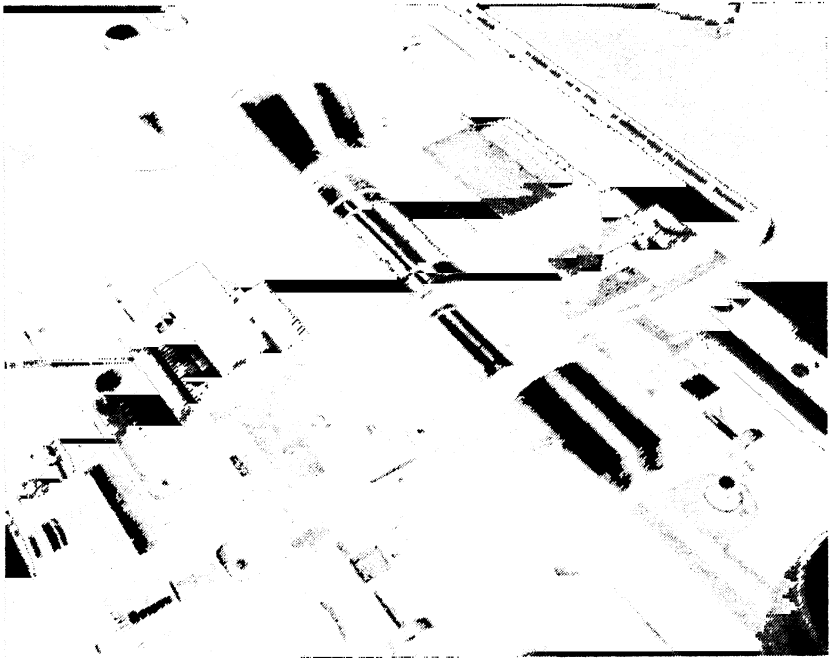
8. Fit three-point steady, using cone support to keep liner true whilst pads are adjusted.

Courtesy Alfred Herbert Ltd

FIG. 55—TOOLING FOR FINNING OPERATION ON I.C.E. CYLINDERS

9. Index pilot bar and feed bar by means of hand wheel until it enters pilot bush in chuck. Finish bore, leaving 0·008–0·010 in. for sizing.

10. Wind pilot back and index turret, and finish cone in mouth of bore.

11. Start size bore for a length of 2 in., using boring bar holder fitted with a fine adjustment toolholder and boring cutter.

12. Size bore with floating cutter head. Supporting bush must be clean and run freely.

From the above list of operations and the size of the work involved, it will be clearly seen that the point made earlier about turret and capstan lathes is demonstrated in this particular case. The reference is to the remark that turret lathes handle heavier and larger work than the capstan.

FIG 56—KNEE TURNING TOOLHOLDER

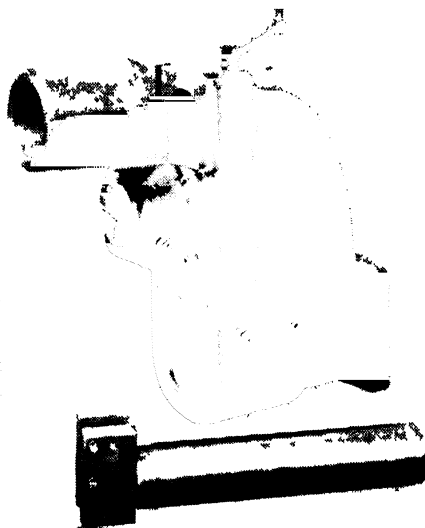



FIG 57—KNEE TOOLHOLDER WITH ADJUSTABLE SLIDE

FIG 58—COMBINATION BORING AND FACING TOOLHOLDER

The tooling for the finning operation on I.C.E. cylinders is shown by the photograph reproduced in Fig. 55.

The toolholders used in the turrets of capstan and turret lathes are generally as indicated in the following illustrations.

Fig. 56 shows an example of a knee turning toolholder.

Fig. 57 illustrates the knee toolholder which incorporates an adjustable slide that obviously increases the usefulness of this attachment.

In Fig. 58 is shown yet another type of toolholder. This is a combination boring and facing toolholder.

All the above toolholders can be obtained in various sizes to suit the work, and can be fitted to the hexagon turret in either capstan or turret lathes.

It will now be clear that fundamentally there is little difference between the capstan and turret lathes. The American machines are distinguished by the names Ram and Saddle-type turret lathes, in which the term ram refers to the slide or ram on which the hexagon turret unit moves, and the term saddle refers to the large saddle hung directly from the lathe bed.

Hence a ram-type turret lathe is the American description of our capstan, and the saddle-type turret lathe the American equivalent of our turret lathe.

In the capstan lathe, the slide being adjustable, the shortest stroke possible for any given component can be set and thus quick tool changes made, the traverses of the hexagon turret being short, whereas in the turret lathe the saddle may have to move the entire bed length.

The turret is usually a machine using a chuck for work holding. The capstan lathe, on the other hand, may be either a bar or chucking machine. The tools for bar work are usually much more rigid, since they can be set entirely within the toolholder, as in the case of the roller toolbox, etc. The chucking machine, on the other hand, calls for tools in the toolholder which may require considerable overhang depending on the work size.

Thus summing up the two types: the capstan is the quicker machine due to its slide. Of the capstan types the bar machine is usually the quicker of the two for the reasons already mentioned. The turret lathe is therefore a heavier, larger lathe devoted to heavy and large work beyond the capacity of the ordinary capstan range of machine.

These are the main classifications, and further subdivision can be made in so far as the cross slide may be of the simple type or compound. However, in the modern types such distinctions are not so pronounced perhaps in view of the possible inclusion in the machine design of units such as taper turning attachments and chasing saddles.

Another point in the comparison of turret and capstan lathes is that neither of these machines has a lead screw in the front of the machine, as is the case with ordinary centre lathes.

Operations requiring screw cutting are performed in the capstan and turret lathes by dieheads held in the turret, or by use of the chasing saddle, as explained in the case of the "Herbert" capstan.

Tolerances held by the Various Types of Machines

The tolerances on work produced by machines is generally of the following order:

Centre lathe .	Diameters ± 0·001 in., length ± 0·001 in.
Capstan lathe .	Diameters ± 0·002 in., length ± 0·005 in.
Milling machine	± 0·002 in.
Shaping machine	± 0·004 in.
Cylindrical grinding machine . . .	± 0·0002 in.
Surface grinding machine	± 0·0004 in.
Internal grinding machine	± 0·00025 in.
Lapping machine	± 0·00005 in.
Jig boring machine	± 0·0001 in.

The above are general figures, and include a fairly comprehensive range of machines. There are individual cases where these figures vary, and they may be less than those given, but on the other hand where wear, misalignment, and other like factors contribute to a poor finish, the figures may well be greater than those cited.

However, they are given in order to provide the student with a comparison which should serve as a reasonable guide to the tolerances on work held by a good percentage of the types of machines in general use.

Exercises on Chapter III

1. Describe the general constructional features of a capstan lathe.

2. With the aid of sketches, describe the turret indexing mechanism of a capstan lathe.

3. What is the difference between a capstan and a turret lathe ?

4. Name three of the types of toolholders commonly used in the hexagon turret of a capstan or turret lathe and sketch one of them.

5. What are the main features of the " Herbert " Preoptive Capstan Lathe ?

6. Sketch the square tool post usually fitted to a capstan or turret lathe, and include a list of the operations usually performed from this unit.

7. Make an operation layout for making a standard ¾-in. British Standard Whitworth bolt on a capstan lathe, and draw the tool layout showing the tool characteristics required for this work. Length of bolt 3½ in. under the head; screwed portion 1½ in. long, chamfered end.

CHAPTER IV

MILLING MACHINES

In milling, the machines for the milling operations fall into three main classes:

1. Horizontal plain milling machine.
2. Vertical milling machine.
3. Universal milling machine.

There are, of course, other machines such as thread milling machines and special adaptations, but the main types fall into the above categories.

Briefly, the plain horizontal milling machine is similar to the surface grinding machine in its operation. The table with the work mounted on it moves in a longitudinal direction with a reciprocating motion under the revolving cutter. The table can be raised and lowered, and can also

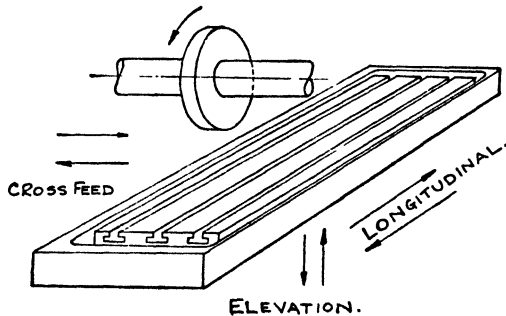



FIG. 59—TABLE MOVEMENTS

be given a cross traverse motion at right angles to this motion and the motion of the table in the longitudinal direction.

Many improvements have been made in milling machine design, and latest improvements incorporate a dial which calculates the speeds, feeds, and cutter diameters for various materials. Machines incorporating this feature are known as dial-type milling machines. The dial can be clearly seen in the illustrations of the milling machines included in this chapter, and details are given along with the illustration of the dial itself.

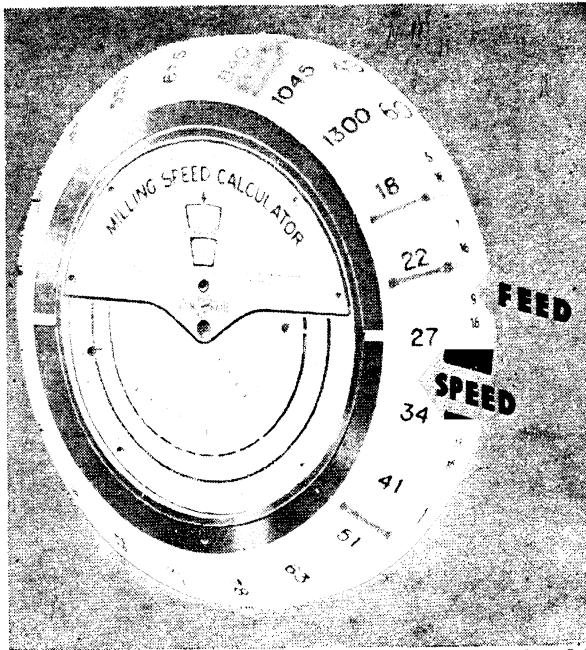
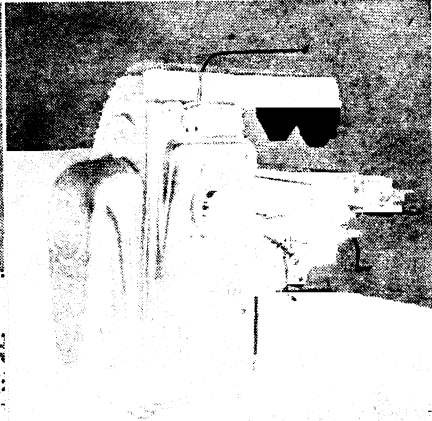
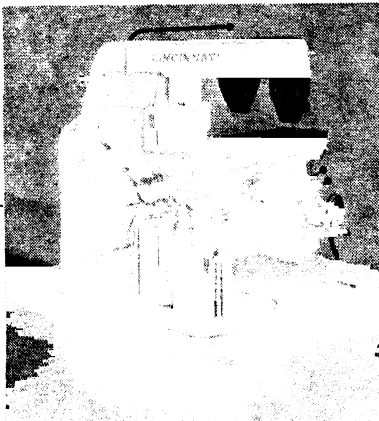
The dial, as can be seen from the illustration, calculates the correct cutting speed, enabling efficient milling and lengthening the cutter life accordingly. By setting the type of cutter and its diameter in the

Courtesy Cincinnati Milling Machines Ltd.

FIG. 60—DIAL INDICATOR

Courtesy Cincinnati Milling Machines Ltd.

FIGS. 61 and 62: HORIZONTAL MILLER

Above: Front view. Right: Rear view.

Courtesy Cincinnati Milling Machines Ltd

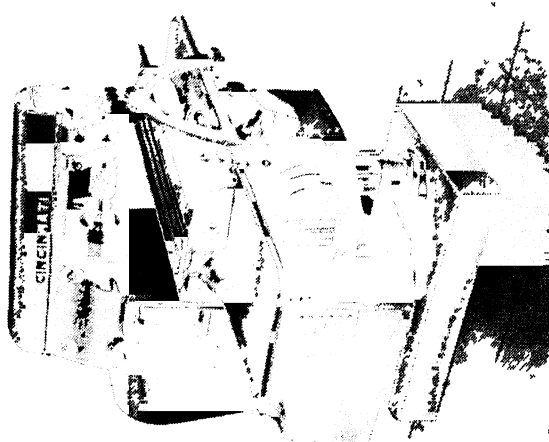
FIG. 63A—GANG MILL SET-UP

Courtesy Cincinnati Milling Machines Ltd.

FIG. 63—MILLING MACHINE SHOWING ARBOR SUPPORTS AND BRACING

windows of the dial, the cutting speed and spindle r.p.m. can be read off on the circular scales. Thus, for a 1½-in. diameter cutter of the cemented or sintered carbide type, the cutting speed is between 270 and 350 ft. per minute and the spindle r.p.m. between 110 and 140, the mean values being 300 ft. per minute and 120 r.p.m. for the above cutter working on tough alloy steel or cast steel. The correct or nearest spindle r.p.m. can now be set on the dial which, as can be seen, surrounds the calculator. This fitment is incorporated in all the types of milling machines—plain, universal, and vertical, and a selective range of speeds and feeds can be easily and progressively obtained.

The following illustrations show modern types of plain horizontal milling machines.

Fig. 63A shows a gang mill set up for milling simultaneously four faces

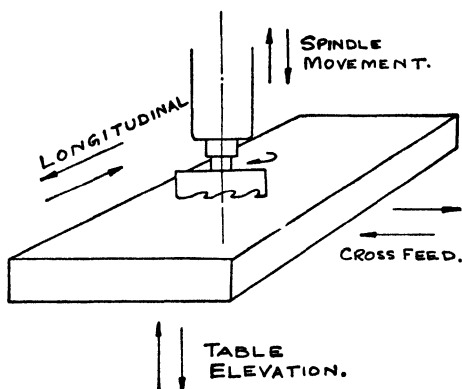



FIG. 64—TABLE MOVEMENTS

of a casting, the general layout being clearly seen from the illustration.

The vertical machine, as its name implies, has a vertical spindle, and apart from this the general principles of the plain horizontal milling machine are applicable here. The table has the same movements of longitudinal traverse, cross traverse, and elevation (raising and lowering). In addition, the cutter mounted on the vertical spindle can also be raised and lowered to suit the work. The motions of the vertical machine are shown in Fig. 64.

The modern type of vertical machine has pleasant lines and enclosed parts, and a typical vertical milling machine is shown in the following illustration (Fig. 65)

The universal milling machine is similar to the plain horizontal miller, but in addition has an added table movement which enables the table to be swivelled about its vertical axis. The swivel of the table, usually up to 30°, enables spiral milling or helical milling to be performed, and the table of this type of machine is provided with a dividing head. This

latter enables work to be indexed and its circumference to be divided up into any number of divisions.

The current model of the universal milling machine of Messrs. Cincinnati Milling Machines Ltd. is shown in Fig. 66.

Another illustration showing a universal milling machine with a dividing head on the table is given in Fig. 67

Attachments

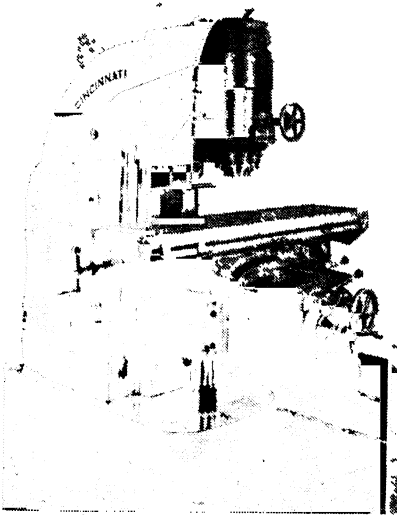
There are a number of attachments, in addition to the dividing head, which can be used in conjunction with this type of machine, including

Courtesy Cincinnati Milling Machines Ltd

FIG. 65—VERTICAL MILLING MACHINE

Courtesy Cincinnati Milling Machines Ltd

FIG. 66—UNIVERSAL MILLING MACHINE

vertical milling attachment, slotting attachment, and grinding attachment. Also overarm and spiral milling attachments can be fitted to horizontal machines. The most used is the vertical spindle attachment, a very useful fitment which converts a horizontal machine into a vertical machine. A typical vertical attachment is shown in Fig. 68 and a spindle attachment in Fig. 68A.

In all cases the machine is self-contained, and from the illustrations given the streamlined effect of the modern machines and their pleasing appearance will be self-evident

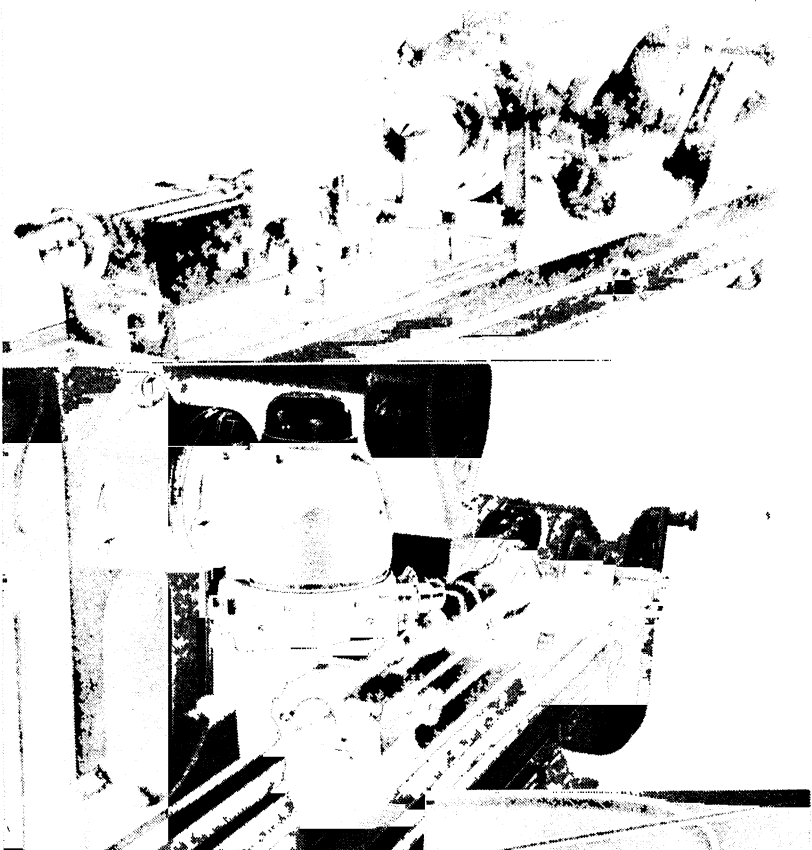
The drive is taken from an electric motor in the base, and here it should be noted that all motions are button controlled, and rapid power traverse available for bringing up the table into the desired positions.

Courtesy Cincinnati Milling Machines Ltd

FIG 67—Top DIVIDING HEAD

FIG 68—Centre VERTICAL ATTACHMENT

FIG 68A—Bottom SPINDLE ATTACHMENT

Details of the spindle and spindle bearings are dealt with in Chapter X.

The actual milling operation and theory underlying a cutting operation can be analysed as follows. the distribution of the forces and components for the case where a single tooth of a milling cutter is in contact with a workpiece is similar to that shown in Chapter VI for orthogonal cutting

(cutting with a plane face and single straight cutting edge). In Figs. 69 *and 69A the action of the cutting tooth in removing the chip of metal*

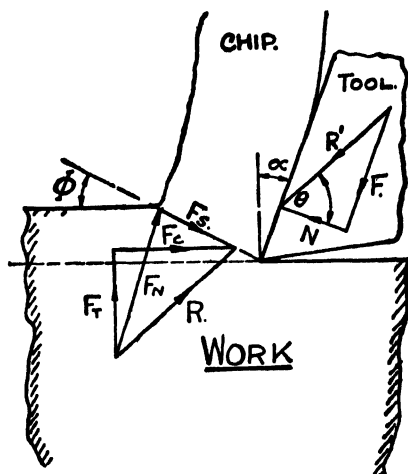



FIG. 69—CUTTING FORCES

shows that the force system holds the chip in equilibrium. The type of chip which is produced depends upon the type of tool-cutting edge and friction between chip metal and face of tool or cutter.

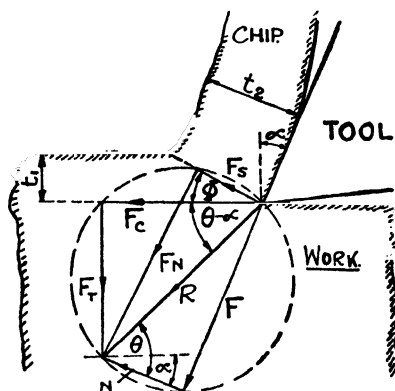



FIG. 69A—CUTTING FORCES (ORTHOGONAL)

The types of chip which are produced generally fall into three classes :

1. Discontinuous or segmental chip ;
2. Continuous chip without built-up edge ;
3. Continuous chip with built-up edge ;

and the formation of the chip is shown in Figs. 69 and 69A.

The relative motion between the cutter and the work is a little more *complex than would appear at first sight, since the cutter centre moves relative to the work at the same time that it is revolving, and the sur*face produced by the cutter will obviously depend on the amount of this relative motion. In general, the surface produced is of the following form, which, as can be seen, is a series of waves, the size of the wave depending on the rotation of cutter and travel of the table.

As the cutter rotates and translates relative to the work, it travels a curved path, the curve being a trochoid, and this motion results in the surface shown in Fig. 69B.

Referring now to Fig. 69A, which is reproduced by the courtesy of Messrs. Cincinnati Milling Machines Ltd., the forces acting in the operation of cutting metal shows that the approach to the problem is to consider the chip as a " separate " body in stable equilibrium under the

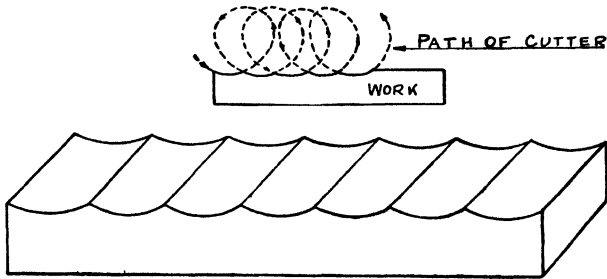



FIG. 69B

action of two equal, opposite, resultant forces, viz. the force which the tool exerts on the back surface of the chip, and the force which the workpiece exerts on the base of the chip (shear plane). The resultant force system for the case of orthogonal cutting (cutting action where the tool generates a plane surface parallel to an original plane surface of the workpiece being machined) is shown in Fig. 69, in which R and R^1 represent the two equal, opposite forces which hold the chip in equilibrium. The force R^1 which the tool exerts on the chip may be resolved along the tool face into the component F (friction force) and component N (the normal force perpendicular to F). The angle θ between N and R^1 is the friction angle, and the force F is the force expended in overcoming friction as the chip slides over the tool face.

Similarly, the force R (of the workpiece on the chip) can be resolved into two components, F_S, shearing force which is responsible for the actual shearing of the metal, and component F_N which exerts a compressive force on the chip at the shear plane. R can also be resolved into forces F_T and F_C. The forces R and R^1 being equal and parallel, and also their individual components, they may therefore be considered as components of a single vector acting at the cutting edge, as shown in Fig. 69A.

The fundamental relationship of force and friction apply equally well here, and we have:

$$\text{Coefficient of friction } \mu = \frac{F}{N} = \tan \theta$$

$$= \frac{F_T + F_C \tan a}{F_C - F_T \tan a}$$

$$F = F_T \cos a + F_C \sin a$$

$$F_S = F_C \cos \phi - F_T \sin \phi$$

Milling

There are two classes of milling, and these are illustrated in Fig. 70. Fig. 70 (A) shows *upcut* or conventional milling and Fig. 70 (B) shows

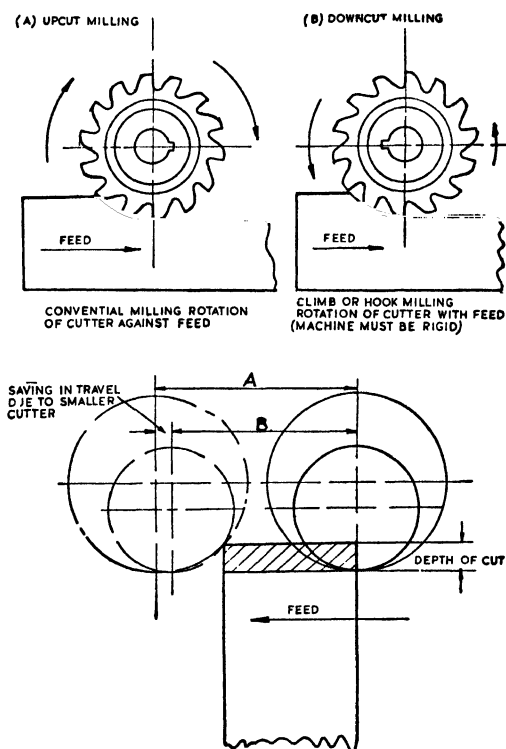



FIG. 70—UPCUT AND DOWNCUT MILLING AND TRAVEL

downcut, climb, or hook milling, in which, since the cut is in the same direction as the feed, a heavier load is imposed on the machine than in conventional milling. It is advisable to use the smallest diameter cutter commensurate with any given operation, as this effects a saving in cutter

travel. The saving due to a smaller diameter cutter is shown in Fig. 70, which shows the travel for two cutters of different sizes.

Now, in the preceding chapter the term " approach " or " start " was used. Let us suppose that a milling cutter of diameter D in. is taking a depth of cut B in., then the approach A can be found thus:

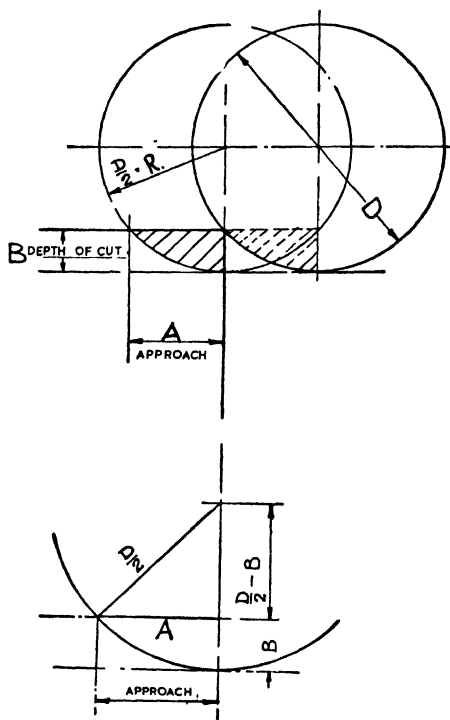



FIG. 71

Referring to Fig. 71:

$$D = \text{Cutter diameter}$$

$$\frac{D}{2} = R = \text{Cutter radius.}$$

$$A^2 = \left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - B\right)^2$$

$$= \frac{D^2}{4} - \left(\frac{D^2}{4} - DB + B^2\right)$$

$$= DB - B^2 = B(D - B)$$

$$\text{i.e. } A^2 = B(D - B)$$

$$\therefore A = \sqrt{B(D - B)}$$

This gives a simple means of finding the amount of approach required for a given depth of cut and diameter of cutter.

The remaining points are covered by reference to Fig. 72, which indicates a milling cutter of diameter D in. having N teeth, operating with a cutting speed of S ft. per minute, and a table feed of F in. per minute. Feed per tooth $= f$, width of cut $= w$, and depth of cut $= d$.

$$\text{Since } S = \frac{\pi D}{12} \times \text{R.P.M.}$$

the number of chips cut per minute will be

$$= \text{R.P.M.} \times N$$

$$= \frac{12S}{\pi D} \times N$$

$$\text{No. of chips per minute} = \frac{12SN}{\pi D}$$

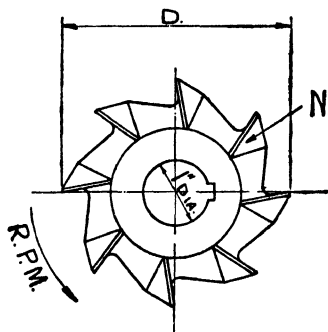



FIG. 72

$$\text{Now the thickness of chip} = T = \frac{\text{Feed}}{\text{No. of chips per minute}}$$

$$\text{i.e. } T = \frac{F}{\dfrac{12NS}{\pi D}}$$

$$\text{Thickness } T = \frac{\pi DF}{12NS}$$

$$\text{Similarly, feed } F = \frac{12NST}{\pi D}$$

Now it is possible to consider the power used in the removal of metal by the cutting process. The horse-power required is given in the following expression:

$$\text{H.P.} = DFSC,$$

where C = Constant, D = Depth of cut, F = Feed, S = Surface speed.

This applies to turning tools and lathe work, but is not suitable for milling operations, since the load varies, depending on whether one, two, or more teeth are cutting at the same time.

Many tests have been carried out, and the following figures, based on the results of practical experience, give values for use in milling:

For 35–40 tons tensile steel:

1 h.p. removes 1 cub. in. of metal per minute with H.S.S. slab mill.
1 h.p. removes 1·6 cub. in. of metal per minute with H.S.S. face cutter.
1 h.p. removes 1 cub. in. of metal per minute with negative rake carbide cutter.

For cast iron approximate hardness 200 Brinell:

1 h.p. removes 2 cub. in. per minute with H.S.S. slab cutter.
1 h.p. removes 3 cub. in. per minute with H.S.S. face cutter.

These values for the constant " C " can now be used for finding horse-power, and using the symbols already given, we can derive the following expressions by substitution in the general expression for horse-power.

$$\text{Horse-power} = \frac{\text{Stock removed per minute in cub. in.}}{\text{Constant C}}$$

$$= \frac{\text{Feed} \times \text{depth} \times \text{width}}{\text{C}}$$

In one revolution of the cutter it will move forward an amount equal to feed (F) divided by r.p.m.

$$\text{i.e. Feed per revolution} = \frac{\text{Feed}}{\text{R.P.M.}} = \frac{F}{\text{R.P.M.}}$$

$$\text{Feed per tooth} = f = \frac{\text{Feed/rev.}}{\text{No. teeth}} = \frac{F}{\text{R.P.M.}\ N}$$

$$\therefore f = \frac{F}{N\ \text{R.P.M.}}$$

$$\therefore \text{H.P.} = \frac{F \times d \,.\, w}{C}$$

$$= \frac{f \times \text{R.P.M.} \times N \times d \times w}{C}$$

$$\text{Since cutting speed } S = \frac{\pi D}{12} \times \text{R.P.M.}$$

$$\text{R.P.M.} = \frac{12S}{\pi D}$$ (We can substitute this in the above equation)

$$\therefore \text{H.P.} = \frac{f \times 12S \times N \times d \,.\, w}{\pi D \times C}$$

$$\text{H.P.} = \frac{12NSf \,.\, d \,.\, w}{\pi DC}$$

The values of the constant C can be obtained from the tables already given, or for general purposes for steel up to 35–40 tons tensile a figure for $C = 0{\cdot}75$ cub. in./h.p./min. can be used.

Both turning and milling feeds can be determined from a consideration of the power required to remove the metal, and, moreover, the foregoing details will also enable an investigation into the question as to whether the machine selected for some operation has enough h.p. available. Another method would be to use the torque available at the driving spindle to find the power available at the cutting edge, and from this determine the pressure on the tool point, from which the area of the cut can be determined; thence the depth of cut and feed rate can be established.

Example.—Find the thickness of chip, r.p.m. of spindle, and number of chips cut per minute for a 4-in. diameter milling cutter having 10 teeth and operating with a table feed of 2 in. per minute if it is cutting steel at 100 ft. per minute:

$$\text{r.p.m.} = \frac{12S}{\pi D}$$

$$= \frac{12 \times 100}{\pi \times 4} = \frac{300}{\pi} = 95{\cdot}5$$

∴ Spindle makes **96 r.p.m.** to nearest round figure.

$$\text{Thickness } T = \frac{\pi DF}{12NS}$$

$$= \frac{\pi \times 4 \times 2}{12 \times 10 \times 100} = \frac{\pi}{1500}$$

∴ $T = 0{\cdot}002094 =$ **0·002 in.** (2 thousandths).

$$\text{Number of chips per minute} = N \times \text{R.P.M.}$$

$$= \frac{12SN}{\pi D}$$

$$= 10 \times 95{\cdot}5$$

$$= \mathbf{955.}$$

In milling, feed is usually given in thousandths of an inch per revolution, and a further example will clarify this point.

Example.—Find the table feed in inches per minute, metal removed per minute, and horse-power required for a milling operation. Depth of cut = 0·1 in.; width of cut = 4 in., and feed rate is 0·03 in. per revolution, and cutter makes 200 r.p.m. when cutting steel.

$$\text{Stock removed per cut} = \text{width} \times \text{depth} \times \text{feed}$$

$$= w \times d \times F$$

$$\text{Feed in inches per minute} = \text{r.p.m.} \times \text{feed per revolution}$$

$$= 200 \times 0{\cdot}03$$

$$= \textbf{6 in. per minute.}$$

Cub. in. of metal removed per minute $= w \times d \times F$

$$= 4 \times 0{\cdot}1 \times 6$$

$$= \mathbf{2{\cdot}4\ cub.\ in.\ per\ minute.}$$

Now, 1 horse-power removes 1 cub. in. of metal per minute ; therefore, to remove 2·4 cub. in. requires 2·4 h.p.

$$\therefore \text{H.P. required} = \mathbf{2\tfrac{1}{2}}$$

From the examples just indicated it is possible to work back from the machine horse-power, and from it find the feed.

The power absorbed in milling operations can be observed in a manner similar to that described in Chapter II for lathes. A wattmeter is wired into the motor circuit, and by taking readings of the power used when cutting and when running light, the actual power required for any particular cutting conditions can be obtained. One such power test and the results obtained from it are as follows :

The milling machine used was a universal type, and the spindle speed was set to 180 r.p.m. The table feed was 2 in. per minute, the cutter diameter $2\frac{1}{2}$ in., depth of cut 0·1 in., face of work being milled $= 2 \times 4$ in., power in cut 2·15 kW, power light 0·65 kW.

$$\text{Power absorbed by cut} = 2{\cdot}1 - 0{\cdot}65$$

$$= \mathbf{1{\cdot}5\ kW}$$

$$\text{Cutting speed } S = \frac{\pi DN}{12}$$

$$= \frac{\pi \times 2\frac{1}{2} \times 180}{12}$$

$$S = \mathbf{118\ ft.\ per\ minute.}$$

Now:

$$\text{H.P.} = \frac{\text{kW}}{0{\cdot}746}$$

$$\therefore \text{H.P.} = \frac{1{\cdot}5}{0{\cdot}746}$$

$$= \mathbf{2.}$$

Also :

$$\text{H.P.} = \frac{\pi DNT}{33000 \times 12}$$

$$\therefore T = \frac{\text{H.P.} \times 33000 \times 12}{\pi DN}$$

$$= \frac{2 \times 33000 \times 12}{\pi \times 2\frac{1}{2} \times 180}$$

$$\therefore T = \mathbf{560\ lb.}$$

The nominal pressure on the teeth of the cutter can be found from the above by dividing by the area of cut as in previous examples ; for side

and face cutters this can readily be accomplished, but for slab mills this is rather difficult owing to the spiral of the teeth.

Indexing

Use of the Dividing Head.—The dividing head is used for obtaining a given number of divisions of the work, chiefly for gears and similar work produced on a milling machine.

There are three types of indexing:

1. Simple indexing.
2. Compound indexing.
3. Differential indexing.

The dividing head employs a single start worm and a 40-tooth worm-wheel, and one of a series of hole or index plates in order to obtain the divisions required. Thus one turn of the crank, and hence one turn of the worm, results in one-fortieth turn of the spindle and one-fortieth turn of the work carried by the spindle. Obviously, for 40 divisions, say a gear with 40 teeth, one turn of the crank would bring one tooth space into line with the cutter, and 40 such turns would complete the revolution of the gear blank.

For other divisions the worm revolutions or part of a revolution are split up by the plates which contain a series of hole circles.

The Brown & Sharpe Dividing Head has three standard plates with the following hole circles:

Plate No. 1	15, 16, 17, 18, 19, 20 holes.
Plate No. 2	21, 23, 27, 29, 31, 33 holes.
Plate No. 3	37, 39, 41, 43, 47, 49 holes.

And the gears for use with the dividing head for differential indexing and spiral milling are as follows:

Teeth . . 24(2), 28, 32, 40, 44, 48, 56, 64, 72, 86, 100.

The Cincinnati and Parkinson Dividing Heads use the following plate, which is a double-sided plate in which holes are provided as follows:

Standard Dividing Head Plate

1st side . . .	24, 25, 28, 30, 34, 37, 38, 39, 41, 42, 43.
2nd side . . .	46, 47, 49, 51, 53, 54, 57, 58, 59, 62, 66.

From the above it will be seen that there are 11 hole circles in each side giving 22 rows of holes from 24 to 66, which can be used to divide the circumference of the work.

The Cincinnati also have a wide range divider for use with the dividing head, and the plates for this are Large Plate for Wide Range Divider:

1st side . .	24, 28, 30, 34, 37, 38, 39, 41, 42, 43, 100.
2nd side . .	46, 47, 49, 51, 53, 54, 57, 58, 59, 62, 66.

In addition to the above, there are available three plates for high number indexing, and the range of holes for these plates is from 26 to 199, the individual plates giving:

		1st Plate	2nd Plate	3rd Plate
1st side	.	30–189	34–197	26–191
2nd side	.	36–199	32–193	28–187

Courtesy Cincinnati Milling Machines Ltd

FIG 73—WIDE-RANGE DIVIDER

The gears available for these dividing heads are usually those given above, which are provided as standard equipment, but additional gears can, of course, be used.

The main parts of a dividing head are shown in sketches (Figs. 74 and 75), showing a section through dividing-head worm and the side index plate.

A section through the work spindle is shown in Fig. 75, and this indicates the front plate on the front of the spindle which can be used for simple and straightforward cases of indexing that can be done without recourse to the side plate or differential indexing.

Simple Indexing

By simple indexing we mean the process of obtaining divisions on the work by using the index plates already referred to and indexing in *one* of the sets of holes contained in the plate in use.

Since the wormwheel has 40 teeth and worm is a single start thread, then 40 turns of crank, and therefore 40 turns of worm, give 1 turn of the

work, or 1 turn of crank (worm) rotates the spindle one-fortieth of a revolution.

If N equal divisions are required on the work, each division will be $\frac{1}{N}$th circumference of the work.

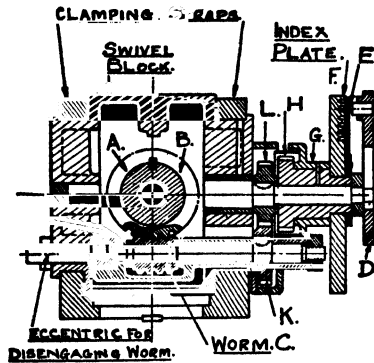



FIG. 74

$$\therefore \text{ No. of turns of crank required} = \frac{40}{N} \text{ per division.}$$

For example, if a shaft is required, say a spline shaft with 6 splines,

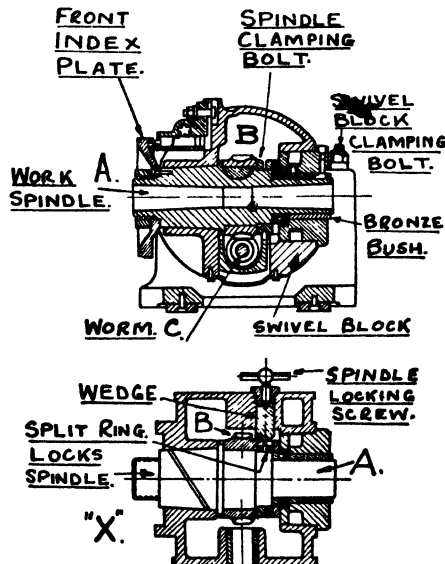



FIG. 75

i.e. 6 divisions, then $N = 6$ as above, and turns of crank required $= \frac{40}{N}$

$$= \frac{40}{6} = 6\frac{2}{3} = 6\frac{16}{24} = 6\frac{14}{21} = 6\frac{22}{33}$$

Therefore, the indexing required will be as follows:

6 whole turns of crank + 16 holes in a 24-hole circle.
6 whole turns of crank + 14 holes in a 21-hole circle.
6 whole turns of crank + 22 holes in a 33-hole circle.

The above indexing is for each division of the work. After one spline has been cut, the crank is turned through 6 turns + 14 holes in a 21-hole circle or its equivalent in any other hole circle, and when this has been done 6 times, the total indexing results in $6 \times 6\frac{14}{21} = 40$ turns, which is 40 turns of crank to 1 of the work. Obviously there are other possible values of the fraction, and the other plates could be used, say:

6 whole turns and 44 holes in a 66-hole circle.
6 whole turns and 26 holes in a 39-hole circle.
6 whole turns and 20 holes in a 30-hole circle.

For 48 divisions the indexing will be:

$$\frac{40}{N} = \frac{40}{48}. \quad \text{Divide by 8, } = \frac{5}{6}$$

The ratio $\frac{5}{6}$ can now be expanded to $\frac{15}{18} = \frac{20}{24}$ and so on.

Thus, simple indexing of 15 holes in a 18-hole circle
20 holes in a 24-hole circle
25 holes in a 30-hole circle

will give the desired indexing, since by taking 48 turns of say 20 holes in the 24-hole plate, we get $\frac{20}{24} \times 48 = 40$ turns, giving the 1 turn of the workpiece as required.

Compound Indexing

This is a method which is employed for divisions of work outside the range of holes provided by the plates and in which the divisions required are obtained by indexing in two steps or stages: (1) By movement of the crank in the usual manner. (2) By the addition or subtraction of a further movement by turning the index plate, controlled by the locking plunger, either in the same direction as the crank or in the opposite way. Suppose the 15 holes in the 18-hole circle for the 48 divisions just found are used, and then the index plate, together with the crank, is indexed a further 3 holes in the 15-hole circle. If both the movements are in the same direction, the total indexing will be:

$$\frac{15}{18} + \frac{3}{15} = \frac{75}{90} + \frac{18}{90} = \frac{93}{90}$$

If the movement were taken in the opposite direction, the total indexing would have been:

$$\frac{15}{18} - \frac{3}{15} = \frac{75}{90} - \frac{18}{90} = \frac{57}{90}$$

By compounding in this way, therefore, it is possible to obtain a large number of divisions.

If the crank is indexed 15 holes in a 20-hole circle, then given a further movement of 2 holes in a 15-hole circle by moving the crank and index plate together, the total indexing will be:

(*a*) Movement in the same direction $= \frac{15}{20} + \frac{2}{15} = \frac{45}{60} + \frac{8}{60} = \frac{53}{60}$

(*b*) Movement in the opposite direction $= \frac{15}{20} - \frac{2}{15} = \frac{45}{60} - \frac{8}{60} = \frac{37}{60}$

In simple indexing it was seen that the indexing required for N divisions is $\frac{40}{N}$, and if now the divisions required are such that simple indexing in the holes cannot be obtained, then the above method of compounding (or differential indexing) must be employed. The fractions which then represent the two movements necessary for the required divisions must give $\frac{40}{N}$ when added or subtracted, and the denominators of the two fractions must be in accord with the hole circles available in the index plates. When the divisions required are of the nature described, the fractions are solved either by trial and error methods or the convergents of continued fractions.

Since most of the dividing heads in present use can be geared for differential indexing, compounding is not much resorted to.

Differential Indexing

This is in effect an automatic method of carrying out compound indexing, in which the index plate is unlocked and then geared back to the spindle. When the spindle is rotated by means of the crank and the worm, then ordinary indexing results. By the addition of a gear train a subsidiary or auxiliary additional movement can be given to the index plate, either to advance by rotating it in the same direction as the crank, or retard by rotating in the opposite direction, as for compound indexing.

Obviously this method is more straightforward and is capable of dealing with a wider and more comprehensive range than compounding.

The problem is to find the indexing and gear ratio necessary to obtain any given number of divisions on the work.

For example, to find the differential indexing for 97 divisions:

The indexing required $= \frac{40}{N} = \frac{40}{97} =$ turns of crank per division

i.e. $\frac{40}{97} \times 97 = 40$ turns of crank to 1 of spindle.

But there is no 97 circle available.

Thus, $\frac{40}{97} = \frac{10}{24}$ approximately $= \frac{10}{24} = \frac{2 \times 5}{4 \times 6} = \frac{24}{48} \times \frac{40}{48}$

or 10 holes in 25 circle and $\frac{40}{48}$ plus two idler wheels to drive plate in same direction as crank.

Thus, since 10 holes in a 24-hole circle, will give

$$\frac{10}{24} \times 97 = \frac{970}{24} = 40\frac{10}{24} \text{ turns.}$$

But only 40 turns are required ; therefore, $\frac{10}{24}$ of a turn must be subtracted, i.e. during the complete 40 turns, $\frac{10}{24}$ turn must be subtracted or $\frac{1}{40} \times \frac{10}{24}$ turn per index of 10 holes in 24 circle, and the gears used can be as already found $\frac{24}{48}$ and $\frac{40}{48}$ or any similar combination which will give this fraction, and this motion must be subtracted from the indexing by rotating the plate in the opposite direction.

Find the indexing for 107 divisions :

$$\frac{40}{N} = \frac{40}{107} \text{ ; cancelling by 5 gives } \frac{8}{21} \text{ nearly}$$

$$\frac{8}{21} \times 107 = \frac{856}{21} = 40\frac{16}{21} \text{ turns of crank,}$$

which is $\frac{16}{21}$ turn too much and therefore must be subtracted, since only 40 turns are required, and the crank must make $\frac{16}{21}$ turn in the opposite direction.

$$\text{Gear ratio for connecting spindle to plate} = \frac{16}{21} = \frac{\text{Drivers}}{\text{Driven}}$$

$$\frac{16}{21} = \frac{8 \times 2}{7 \times 3} = \frac{64}{56} \times \frac{32}{48}$$

$\therefore$ Indexing is 16 holes in a 21-hole plate with gear ratio $\frac{64}{56} \times \frac{32}{48}$ driving crank in the opposite direction.

Example.—The crank of a dividing head is turned through N holes in an A circle, and then the plate is indexed a further n holes in a B circle in the same direction. Using these symbols, find an expression for the indexing obtained.

Clearly the fraction is $\frac{N}{A} + \frac{n}{B}$

Take a common denominator :

$$\text{Then } \frac{N}{A} + \frac{n}{B} = \frac{BN + An}{AB} = \frac{NB + nA}{AB}$$

Now the crank moves 40 turns to 1 of work spindle.

$$\therefore \frac{40}{1} = \frac{NB + nA}{AB}$$

$$40AB = 1\ (NB + nA)$$

$$\therefore \text{For 1 turn of crank indexing} = \frac{40AB}{NB + nA}$$

To verify this result, let us consider the indexing for 91 divisions which, by compounding, are given by taking 6 holes in a 39-hole circle plus 14 holes in a 49-hole circle.

Here $N = 6$; $A = 39$; $n = 14$; $B = 49$.

$$\therefore \text{Indexing} = \frac{40AB}{NB + nA}$$

$$= \frac{40 \times 39 \times 49}{6 \times 49 + 14 \times 39}$$

$$= \frac{76440}{294 + 546}$$

$$= \frac{7644}{84}$$

$$= \mathbf{91.}$$

Sometimes the indexing is required in degrees. Since 1 turn of the work represents a movement of 360°, the ratio

1 turn of work to turns of crank $= \frac{1}{40} = \frac{360}{40} = 9°$

that is, 1 turn of crank represents 9° movement of the work, and $1° = \frac{1}{9}$ turn of crank,

i.e. $\frac{1}{9} = \frac{6}{54}$, i.e. 6 holes in a 54-hole circle = 1° on work

and $\therefore$ 1 hole in 54 circle $= \frac{1}{6}° = 10$ min.

Indexing involving this method is known as angular indexing.

The operation of the dividing head is briefly as follows: referring to Figs. 74 and 75, the spindle A is screwed at one end "x" to take a chuck or driving plate for the work and carries a wormwheel B having 40 teeth. A single-thread worm C meshes with wheel B, and handle D is geared to the wormshaft. The spring-loaded plunger E can be adjusted radially to engage with any desired circle of holes in the index plate F (side plate), which is attached to a shaft carried in a boss, and the index plate can be locked to the casing when required by a locking plunger. It can also be driven by a gear H from a shaft P (not indicated) which is horizontal and perpendicular to the wormshaft. When shaft P is geared to the lead screw of the machine, the rotational motion of the spindle A can be correlated to the linear travel of the table and the dividing head. If wheel H and therefore plate F are fixed, then by disengaging plunger E and turning crank D until the plunger E can be engaged in another hole, the crank D will be turned through an angular step the value of which will depend on the number of holes in the circle and the number of holes taken in this circle. For instance, if the plunger is engaged in the 18-hole circle and moves 2 holes along, the crank will move through an angle equal to

$$\frac{360}{18} \times 2 = 40°$$

and the spindle A will move $\frac{1}{40}$ of this, or 1°.

If n = number of holes moved and N = number of holes in the circle, then spindle and work movement

$$= \frac{360}{40} \times \frac{n}{N} = \frac{360n}{40N}$$

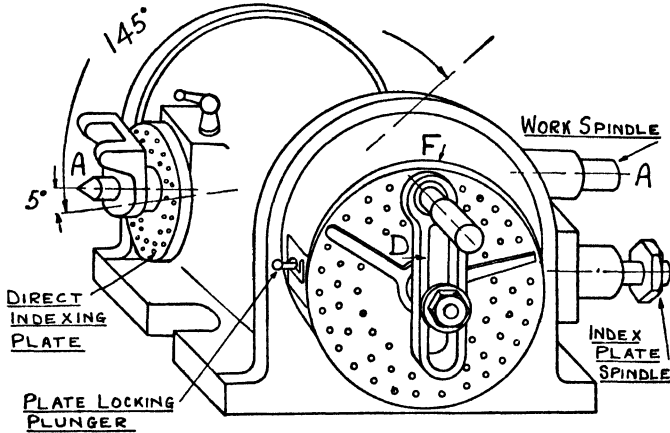



FIG. 76

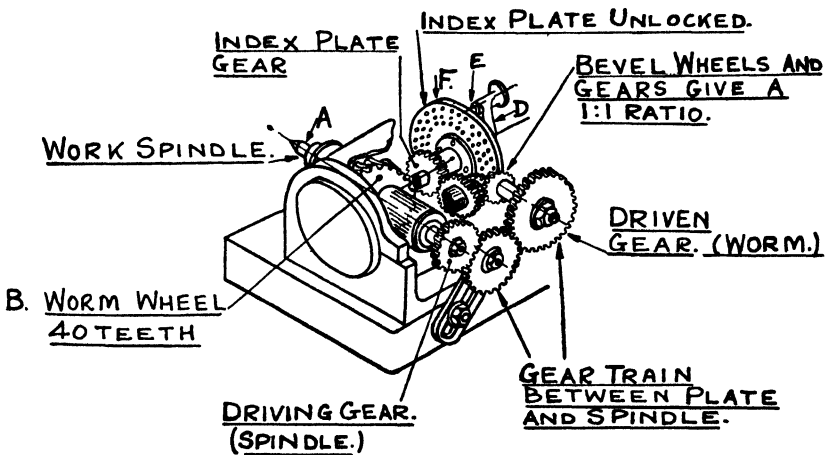



FIG. 77—DIVIDING HEAD SHOWING GEARS FOR USE IN DIFFERENTIAL INDEXING

For the above this gives $\frac{\overset{18}{\cancel{360}}}{\underset{20}{\cancel{40}}} \times \frac{\cancel{2}}{18} = 1°$ as before.

If the dividing head is geared for differential indexing, a typical arrangement would be as shown in Fig. 77. Let the gear ratio between the work

spindle A and the Plate $F = R$, such that one revolution of A is equivalent to $\frac{1}{R}$ revolutions of F. Then if the gear train is such that it moves plate F in the same direction as crank D, the motion of A in degrees is given by:

$$\text{Motion of } A = \theta^\circ = \frac{360nR}{N\ (40R - 1)}$$

and the divisions on the work circumference $= \frac{360}{\theta}$

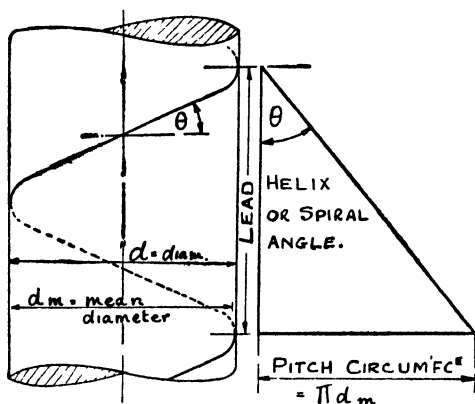



FIG 78.

$$\text{i.e.} \quad \begin{matrix}\text{No. of Divisions}\\ \text{(indexing)}\end{matrix} = \frac{360}{\frac{360nR}{N\ (40R - 1)}} = \frac{N\ (40R - 1)}{nR}$$

using the same notation as before for N and n, i.e. N = number of holes in circle, n = number of holes moved.

Spiral Milling

In spiral or helical milling the dividing head is geared to the table leadscrew, and it is first necessary to find the lead of the machine, which is the lead of the helix that the machine would cut if the table leadscrew were connected to the worm of the dividing head by a straight 1 : 1 gear ratio. If this were done, since it takes 40 turns of the worm to turn the work through 1 turn, the leadscrew of the machine will also make 40 turns (due to 1 : 1 ratio) and the machine table will have advanced a distance equal to 40 times the pitch of leadscrew. This table movement is the " lead of the machine ":

i.e. lead of machine = 40 times pitch of leadscrew.

If n = No. of threads in leadscrew,

$$\text{pitch of leadscrew} = \frac{1}{n}$$

$$\therefore \text{ lead of machine} = 40 \times \frac{1}{n} = \frac{40}{n}$$

Most machines have a leadscrew of 4 threads per inch.

$\therefore$ lead of machine $= \frac{40}{4} = 10$ in.

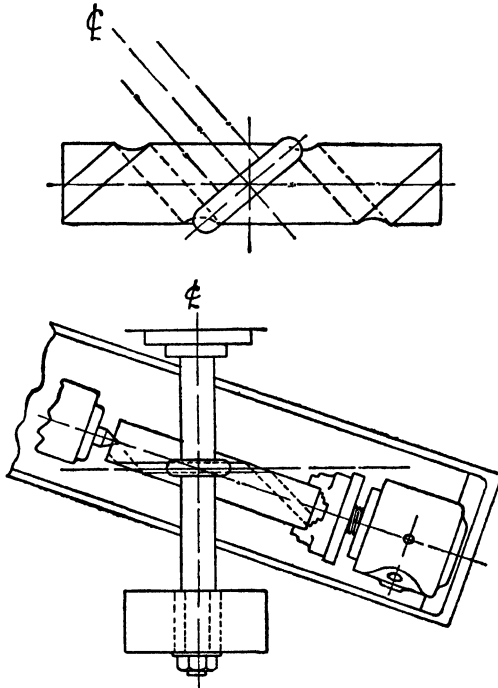



FIG. 79—SPIRAL MILLING SHOWING SETTING FOR HELIX

If n is any other value, the lead must be calculated using the expression given above.

Now with the lead of the machine known, the gears required to cut a helix of any given lead can be determined as follows:

$$\text{Ratio}: \frac{\text{DRIVERS}}{\text{DRIVEN}} = \frac{\text{LEAD OF MACHINE}}{\text{LEAD OF HELIX TO BE CUT}}$$

Helices can be right-hand or left-hand, depending on which way the work is rotated, and this is controlled by the presence or otherwise of an idler gear in the train between machine leadscrew and dividing head.

Referring to Fig. 78:

$$\tan\theta = \frac{\text{Pitch circumference}}{\text{Lead}} = \frac{\pi dm}{\text{Lead}}$$

When the helix angle is obtained, either the cutter or the table must be swung round so that the cutter lies at the angle θ relative to the work (see Figs. 78 and 79).

Example.—A gear has a pitch circle diameter (p.c.d.) of 4·2 in. and a lead of spiral of 17·2 in. Find suitable gear ratio and helix angle for setting. Machine leadscrew = 4 T.P.I.

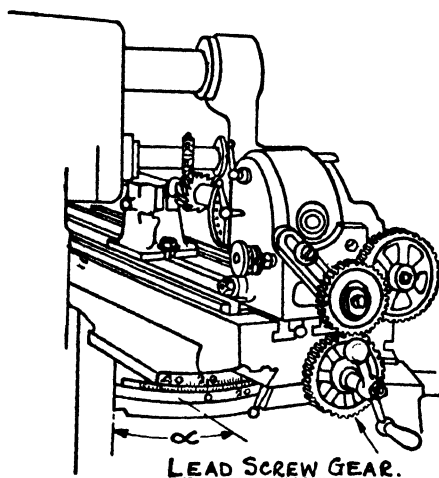



FIG. 80—UNIVERSAL MILLING MACHINE WITH TABLE SET OVER AND DIVIDING HEAD GEARED FOR MILLING SPIRAL CUTTER

$$\text{Gear ratio} = \frac{\text{DRIVERS}}{\text{DRIVEN}} = \frac{\text{LEAD OF MACHINE}}{17{\cdot}2}$$

$$= \frac{10}{17{\cdot}2} = \frac{100}{172} = \frac{100 \times 1}{86 \times 2}$$

$$\text{Gear ratio} = \tfrac{100}{86} \times \tfrac{24}{48}$$

Tan of helix angle θ,

$$\tan\theta = \frac{\pi dm}{\text{Lead}} = \frac{\pi \times 4{\cdot}2}{17{\cdot}2} = \frac{13{\cdot}2964}{17{\cdot}2}$$

$$\tan\theta = 0{\cdot}7727$$

$$\therefore \theta = 37^\circ\ 42'$$

$$Since\ tan\ \theta = \frac{\pi dm}{Lead}\ it\ follows\ that$$

$$Lead \times tan\ \theta = \pi dm$$

$$\text{Lead} = \frac{\pi dm}{\tan \theta}$$

and the lead or any other factor can be found from a manipulation of the factors. It will also be noted that the mean diameter is used for finding the helix angle. This is because the angle varies with the diameter, and if the groove being cut is a deep one, there will be some variation between the angles calculated, using the diameters taken at the top and bottom of the grooves, and it is best to take the mean diameter unless some other consideration fixes the choice.

Fig. 80 shows a spiral-tooth milling cutter being machined. The machine table is swung round to the desired angle, and the dividing head geared to the lead-screw. The relationship between work and cutter is further clarified in Fig. 79.

It is not always necessary to swing the table round. The spiral milling of gear teeth can be performed by using the vertical head attachment.

FIG. 81—MILLING HELICAL GEAR USING VERTICAL HEAD ATTACHMENT

When the vertical head has been fitted to the machine it is tilted to the required angle so that the cutter is in the correct position relative to the work and the dividing head is set for the indexing and desired movement.

A typical set-up is shown in Fig. 81.

Cam Milling

Another use of the vertical head is that of cam milling (see Fig. 82, and illustration of milling machine set for cam milling shown in Fig. 83).

Referring to Fig. 82, let:

a = Angle of inclination of dividing head.
R = Gear ratio between leadscrew and dividing-head worm.
n = No. of threads per inch (T.P.I.) on leadscrew.
l = Lead of cam to be milled.

For 1 turn of the table leadscrew the dividing-head worm will make R turns, and due to the 40 : 1 reduction between the worm and spindle, the work will make $\frac{R}{40}$ turns.

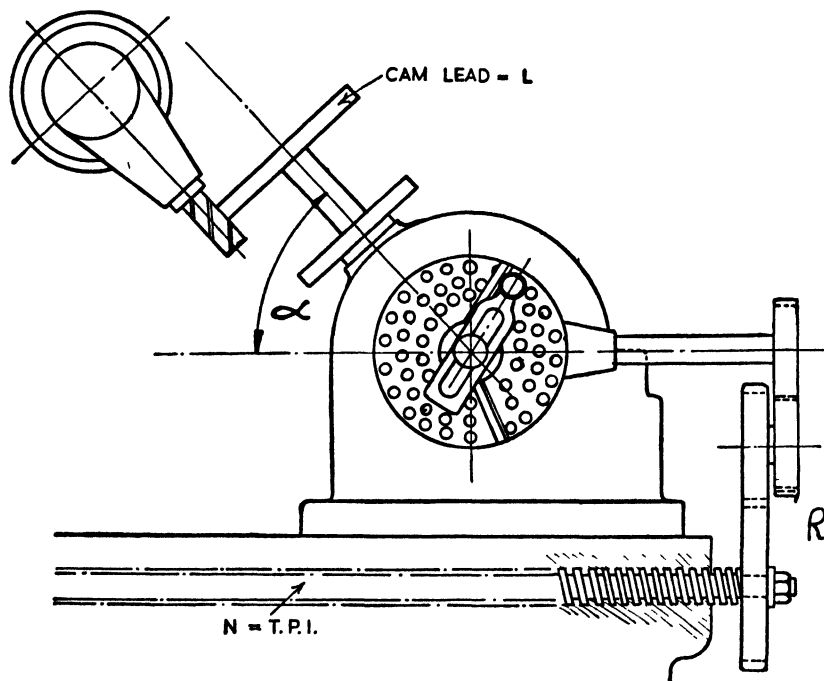



FIG. 82—CAM MILLING

Hence, in 1 turn of the leadscrew the table will advance a distance $= \frac{1}{n}$ in.

$$\frac{\text{Revolutions or turns of the work}}{\text{Movement of table}} = \frac{\frac{R}{40}}{\frac{1}{n}} = \frac{Rn}{40}$$

$$\text{Revolutions of work} = \frac{Rn}{40} \times \text{table movement}$$

For 1 revolution of work :

$$1 = \frac{Rn}{40} \times \text{table travel.}$$

If $n = 4$ (the usual value of T.P.I. for leadscrew)

then table movement $= \frac{40}{Rn}$ per revolution of work.

If T = Table travel,

$$T = \frac{40}{Rn} = \frac{40}{4R} = \frac{10}{R} \text{ for 4 T.P.I. screws.}$$

Courtesy Cincinnati Milling Machines Ltd

FIG 83—CAM MILLING WITH VERTICAL SPINDLE

Now the lead of the cam to be cut is related to the inclination of the dividing head and the gear ratio R between the leadscrew and worm, and when an awkward gear ratio results from the calculation, a different value of R or a more suitable ratio, say 2 or 3, can be used and the inclination α found to suit this gear ratio.

The following sketch shows the relationship between the table movement, the lead to be cut, and angle α.

Referring to this sketch we have:

$$\frac{ac}{cb} = \sin a$$

i.e.
$$\frac{\text{Lead } l}{\text{Table travel } T} = \sin a$$

$$\text{But table movement} = \frac{\text{Lead}}{\sin a}$$

$$\text{and also } T = \frac{40}{nR} = \frac{10}{R}$$

i.e.
$$\frac{10}{R} = \frac{l}{\sin a}$$

$$\therefore R = \frac{10 \sin a}{l}$$

(for $n = 4$ T.P.I.)

or
$$R = \frac{40 \sin a}{nl}$$

(If n is not 4 T.P.I., value of n must be inserted here.)

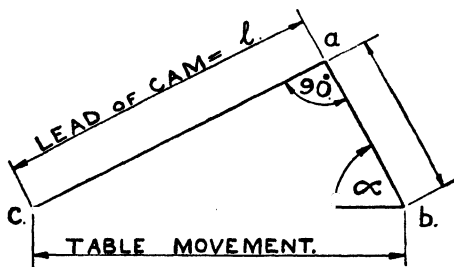



Fig. 84

Example.—Determine a suitable arrangement for the milling of a cam which has a rise of 0·675 in 120° of its angular motion. Table lead-screw 4 T.P.I. Assume a gear ratio R of 2 : 1.

First find the lead of the cam, i.e. find the total rise or fall in 360° movement, or the rise it would have in 360°.

$$\text{Lead } l = 0{\cdot}675 \text{ in. in } 120°$$

$$= \frac{0{\cdot}675 \times 360}{120} = 3 \times 0{\cdot}675$$

$$l = \mathbf{2{\cdot}025 \text{ in.}}$$

$$\text{Now } R = \frac{40 \sin a}{nl}$$

$$2 = \frac{40 \sin a}{4 \times 2{\cdot}025}$$

$$2 = \frac{10 \sin a}{2{\cdot}025}$$

$$\sin a = \frac{4{\cdot}05}{10}$$

$$\sin a = 0{\cdot}405, \text{ i.e. } a = \sin^{-1} 0{\cdot}405$$

$$\therefore a = \mathbf{23^\circ\ 54'}$$

Suppose the setting had been fixed for 30°, what would the gear ratio have to be? Conditions as above:

$$R = \frac{10 \sin a}{l} = \frac{10 \sin 30}{2{\cdot}025}$$

$$R = \frac{10 \times {\cdot}5}{2{\cdot}025} = \frac{5}{2{\cdot}025}$$

$$\therefore \text{Gear ratio } R = \mathbf{2{\cdot}469.}$$

It will readily be appreciated that awkward gear ratios would result if either the lead l or inclination a were to be fixed, and that by adjusting the dividing-head inclination, and incidentally the lead in relation to the table travel, a given gear ratio can be accommodated.

The cams for automatic machines are marked in hundredths, and the lead for these cams is found in the same manner as for degrees in the case of the ordinary-type cam. Suppose a cam has a rise of 2·493 in. in $\frac{47}{100}$ of the cam travel, the lead will be

$$\tfrac{100}{47} \times 2{\cdot}493 \text{ in.} = \mathbf{5{\cdot}304 \text{ in.}}$$

In some instances the cams used on automatic machines have lobes with different rises incorporated in the same cam profile. Such a cam is shown in Fig. 85.

Let the cam profile have a rise of 2·234 in. in $\frac{45}{100}$, and then a further rise of 2·125 in. in $\frac{28}{100}$. Find a suitable setting for the head for milling this cam profile.

First find the leads.

$$\text{Lead on first lobe} = \tfrac{100}{45} \times 2{\cdot}234 = \frac{223{\cdot}4}{45} \text{ in.}$$

$$l = \mathbf{4{\cdot}965 \text{ in.}}$$

$$\text{Lead on second lobe} = \tfrac{100}{28} \times 2{\cdot}125 = \frac{212{\cdot}5}{28} \text{ in.}$$

$$= \mathbf{7{\cdot}588 \text{ in.}}$$

Now there are two leads, and it is usual to take the largest lead and work out the gear ratio or inclination for this one first; mill the lobe and then adjust the head for the remaining lobe.

Assume a gear ratio of 2 : 1 for R and n = 4.

$$R = \frac{40 \sin a}{ln} = \frac{10 \sin a}{l}$$

$$2 = \frac{10 \sin a}{7{\cdot}588} \quad \text{i.e. } 10 \sin a = 2 \times 7{\cdot}588$$

$$\sin a = \frac{15{\cdot}176}{10} = 1{\cdot}5176$$

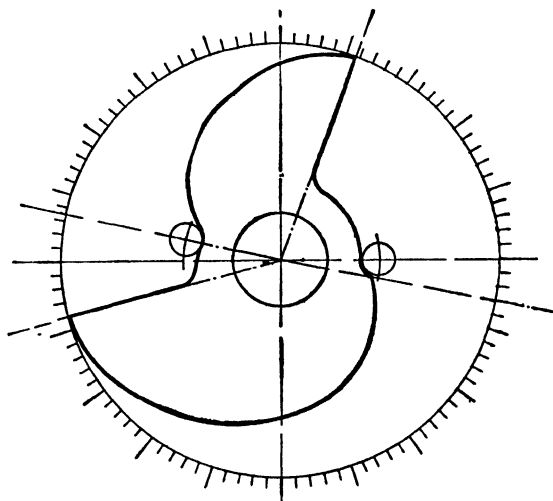



FIG. 85—TWO-LOBE CAM

This, as can be seen, does not give a result which can be applied to the problem, but a 1 : 1 gear ratio would. Taking R = 1 :

$$10 \sin a = 1 \times 7{\cdot}588$$

$$\sin a = 0{\cdot}7588$$

$$a_1 = \mathbf{49^\circ\ 21'}$$

Similarly, $a_2 = \mathbf{29^\circ\ 46'}$

Thus we have two values for a, and the dividing head with a 1 : 1 ratio, as explained, could be set first to 49° 21′ and the first lobe milled, and then the head lowered to 29° 46′ and the second lobe milled or, if preferred, the first setting could be 29° 46′ for the smaller lead and then the head inclination increased to 49° 21′ for the other lead. Of course, the manufacturers of the milling machines provide tables of leads for use with the dividing head and milling machine, and if these are available, and if the lead required is listed, then the setting given can be taken from the tables. If the exact lead required is not contained in the tables, then the nearest

lead above the one desired should be taken and the angle worked out from that, viz.:

$$\frac{\text{Lead required}}{\text{Nearest lead in table}} = \sin \alpha$$

In the Cincinnati table of leads there is a setting for 4·967 and 7·589, this latter probably being near enough for all practical purposes without modification, and the gears given could be used. Where a difference sufficiently large exists, then the gears could be calculated from:

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{\text{Lead}}{10} = \frac{7{\cdot}588}{10} = 0{\cdot}7588$$

and gears, either simple or compound, calculated to give this fraction.

Again, a setting, i.e. gears for a lead fairly close to the one required, could be chosen, and by dividing this into the lead required sin α found as above.

When milling cams, it will be more profitable to have the setting as shown in Fig. 82, in which the cutter is placed under the cam blank. This will enable a clear and uninterrupted view of the cam profile during cutting, and also the chips and swarf will fall clear and not lie on the face of the cam. It also brings the cutter nearer to the table and gives more rigidity.

A useful method for finding the gear ratio R of the train of wheels between index plate and work spindle is as follows, the method, of course, applying to differential indexing:

Let x = Number of divisions required.
N = Number of holes in index-plate circle.
n = Number of holes taken in hole plate at each indexing.
V = Ratio of gearing between index crank and spindle.
R = Ratio of gear train between index plate and spindle.

$$R = \frac{NV - xn}{N}, \text{ when } NV \text{ is greater than } xn$$

$$R = \frac{xn - NV}{N}, \text{ when } xn \text{ is greater than } NV$$

$$R = \frac{\text{Gear on spindle}}{\text{Gear on worm}} = \frac{S}{W} \text{ (simple train)}$$

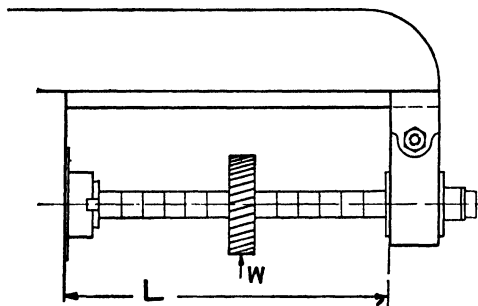
$$R = \frac{S 1_G}{2_G W} \text{ (compound train)}$$

where S = Gear on spindle,
W = Gear on worm,
1_G = 1st gear on stud,
2_G = 2nd gear on stud;

$$\text{i.e. } \frac{NV - xn}{N} = \frac{S 1_G}{2_G W} = \frac{S}{2_G} \times \frac{1_G}{W}$$

It might be permitted, as a conclusion to this chapter, to mention the conditions relating to the milling-machine arbor. Obviously this plays a very important part in the accuracy of the work produced by the machine. If the arbor is bent, buckled, or otherwise out of alignment, the cutter which is mounted on it will not generate true surfaces and undoubtedly will accelerate cutter wear. Moreover, if the arbor is not rigid enough for the duty imposed, chatter or vibration will result, since chatter is a function of arbor deflection. Thus, for a weak or non-rigid arbor the deflection will be increased and chatter will result.

FIG. 86

Referring to Fig. 86, which represents a milling-machine arbor and its supports, it will be seen that a close approximation to the arbor deflection can be found by considering the arbor as a beam supported at its ends, at one end by the column and by the steady at the other.

If W = Load (tooth pressure),
L = Length between supports,
E = Young's modulus for material of arbor,
I = Moment of inertia of arbor (cross section),
δ = Deflection ;

$$\text{then } \delta = \frac{WL^3}{48EI}$$

By substituting the values relating to a particular setting for a given machine, the deflection of the arbor can be found. For a circular cross section the value of I can be found from

$$I = \frac{\pi}{64} d^4$$

where d is the arbor diameter.

As an illustration, we can find the deflection at the centre of an arbor whose unsupported length is 12 in., diameter $1\frac{1}{4}$ in., if E is 30×10^6 lb. per square inch for the material from which arbor is made, for a tooth load of 500 lb.

$$\text{Thus } \delta = \frac{WL^3}{48EI}$$

$$= \frac{500 \times 12^3}{48 \times 30 \times 10^6 \times 0{\cdot}1198}$$

$$\boldsymbol{\delta = 0{\cdot}005 \text{ in.} = 5 \text{ thou. in.}}$$

In some cases it is thought that the arbor is more a built-in beam than a beam supported at each end. If this be the case, the deflection is given by

$$\delta = \frac{WL^3}{192EI} \text{ at centre of span.}$$

Exercises on Chapter IV

1. Describe the main types of milling machines and indicate the table movements.

2. Calculate (*a*) the chip thickness, (*b*) spindle r.p.m., (*c*) number of chips cut per minute, and (*d*) the approach for a milling operation in which the cutting speed $S = 120$ ft. per minute, cutter diameter $= 3\frac{1}{2}$ in., number of teeth $= 16$, and table feed is 2 in. per minute. Cut $\frac{1}{8}$ in. deep.

3. If the cutter in Question 2 is a slab milling cutter $2\frac{1}{2}$ in. long, and it is milling a steel (M.S.) block 2×8 in. with a depth of cut $= 0{\cdot}1$ in., calculate (*a*) cubic inches of metal removed per minute, and (*b*) per h.p. per minute, and (*c*) the cutting time.

4. Taking conditions as given in previous examples, viz. cutter $3\frac{1}{2}$ in. diameter operating at 120 ft. per minute, find (*a*) the h.p. and (*b*) tangential force on the tool (cutter) if the wattmeter readings are 0·35 when running light and 1·65 when in cut.

5. Describe the main features in the operation of a dividing head, giving particular attention to the relationship between the index plate, crank, and work spindle.

6. Calculate the indexing for the following divisions, using Brown & Sharpe plates: (*a*) 595, (*b*) 597, (*c*) 643, (*d*) 701.

7. Describe simple, compound, and differential indexing.

8. The crank of a dividing head is moved N holes in a C circle, and then n holes in a D circle in the opposite direction. Using these symbols, find an expression for the indexing obtained.

9. Describe angular indexing, and give the value in degrees of the divisions obtained: (*a*) per whole turn of the crank; (*b*) for 9 holes in an 18-hole plate; (*c*) for 1 hole in a 21-hole plate.

10. Calculate the indexing for 1,440 divisions. What is the value of each division in degrees ?

11. Describe the methods by which a spiral milling cutter can be produced, and sketch the layout for the work and cutter producing it.

12. Calculate the indexing for the following divisions: 101, 127, 131, and 189 for (*a*) Brown & Sharpe plates, (*b*) Cincinnati plates.

13. Calculate the indexing for the following angles on a Brown & Sharpe dividing head: (*a*) 10°, 20°, $\frac{1}{4}$°; (*b*) 18°, $\frac{1}{4}$°, 1° on a Cincinnati head.

14. What is the lead of a cam which rises 1·105 in. in 115° ? Calculate the setting for milling this cam on a milling machine with a 4 T.P.I. leadscrew.

15. Sketch the layout for producing a cam on the milling machine, and by choosing suitable symbols find the relationship between the leadscrew, cam lead, and dividing-head gear, and its inclination.

16. Calculate the deflection at the centre of span of a milling machine arbor considered as a beam: (*a*) Supported at each end, (*b*) As a built-in beam. Length of span in each case 12 in., load 1,000 lb., arbor $1\frac{1}{4}$ in. diameter. Modulus of elasticity of arbor material $E = 30 \times 10^6$ lb. per square inch.

17. If a milling machine arbor is 15 in. between supports, and is not to deflect more than $\frac{1}{1000}$ in. at its mid-span, what is the maximum load which can be imposed by the cutter ? Take Young's modulus $E = 30 \times 10^6$ lb. per square inch, arbor diameter $1\frac{1}{4}$ in.

18. Repeat the above question, assuming the arbor to be a built-in beam

19. Describe the effects of the deflection of a milling-machine arbor.

CHAPTER V

GRINDING MACHINES

Theory of Grinding

THE application of grinding to engineering production has kept pace with other machining method advances, and many operations have now become standardised grinding operations. It is not so long ago that to speak of grinding meant reference to the work performed on the old grindstone, the large natural stone running in a trough of water, usually at what is now a very low speed. Nowadays we have surface grinders, cylinder-bore grinders, external grinders, universal grinders, thread grinders, profile grinders, gear grinders, centreless internal and external grinders, gagematic grinders, and tool and cutter grinders.

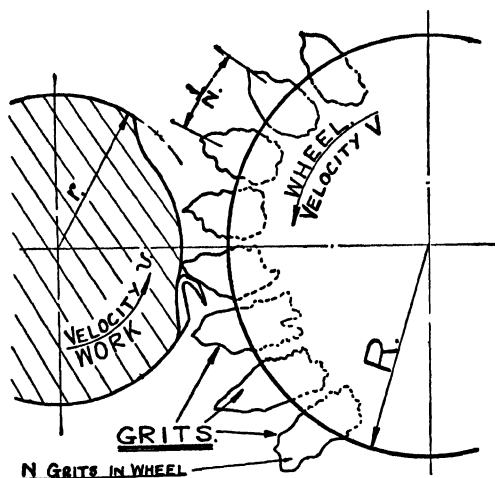



FIG. 87

The action of grinding is, of course, similar in each case, and several grinding theories explain this grinding action in its application to metal removal. Sketched in Figs. 87 and 88 is the exaggerated condition between the wheel and work when grinding.

Of the grinding theories perhaps the better known is the Guest Grinding Theory.

Let V = Velocity of grinding wheel.

N = Number of grits $\therefore$ pitch of grits $= \frac{1}{N}$

v = Velocity of work.

R = Radius of wheel.

r = Radius of work.

Then the time for one grit in grinding wheel to reach a given point after preceding one passes the same point is given by :

$$\text{Time } T = \frac{1}{NV}$$

The normal velocity v_1 (see Fig. 88, A) and v_2 (see Fig. 88, B), when multiplied by this time, equals t, the chip thickness :

$$t_1 = \frac{v_1}{NV}; \quad t_2 = \frac{v_2}{NV}$$

A t₁ v t₁ WORK V A A-B v v₁ V B v· WORK VELOCITY V· WHEEL (GRIT) VEL' WORK PITCH OF GRITS = 1/N v A t₂ V t₂ B V v v₂ A+B

(A) (B)

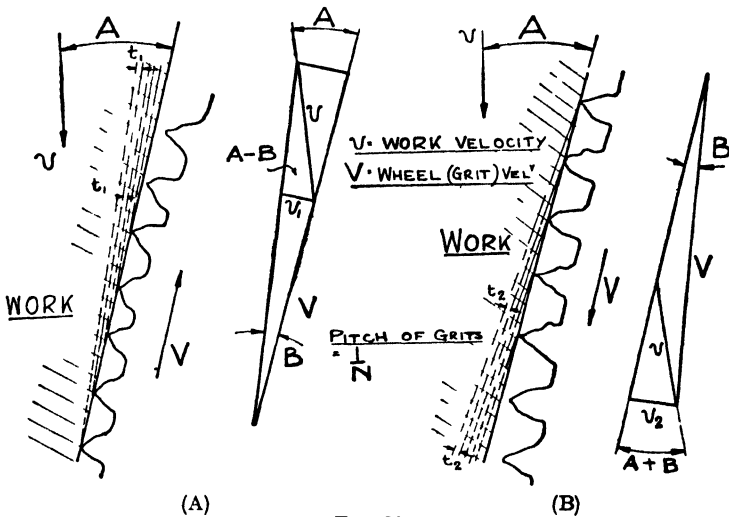



FIG 88

Now, from the relative velocity diagrams

$$v_1 = v \sin (A - B)$$
$$v_2 = v \sin (A + B)$$

Since the angle B is very small, it can be neglected, and t therefore becomes

$$t = \frac{v \sin A}{VN}$$

In the case of cylindrical grinding (external), the time for one grit to reach the same point as its predecessor is as before $T = \frac{1}{NV}$, and referring to Fig. 89, it will be seen that the normal velocity v_1 is

$$v_1 = v \sin (C + D)$$

$$\text{and therefore } t = \frac{v \sin (C + D)}{VN}$$

If the depth of cut $= d$, i.e. diametral reduction is d and depth of

actual grinding cut $= \frac{d}{2}$, the above formula for t can be expanded by finding $\cos\,(C + D)$ in terms of $\frac{d}{2}$; R and v, by use of the Cosine Rule.

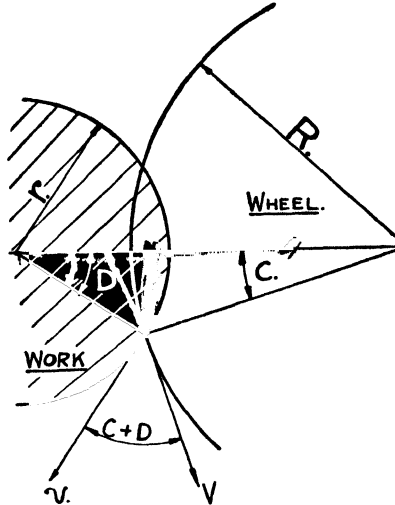



FIG. 89

By the Cosine Rule:

$$\cos\,(C + D) = 1 \left(\frac{R + rd}{Rr2}\right) + \frac{d^2}{8Rr}$$

$$\cos\,(C + D) = 1 \frac{(C + D)^2}{2} + \frac{(C + D)^4}{.\,24}$$

$$\therefore\ (C + D)^2 = \frac{R + r}{Rr} \times d$$

These angles C and D are small, and for small angles in circular measure $\sin \theta = \theta$; therefore, $\sin D = D$, and $\sin\,(C + D)$ equals $C + D$, and substituting this in $\frac{v \sin\,(C + D)}{VN}$ we get:

$$t = \frac{v}{VN} \sqrt{\frac{R + r}{Rr}}\,.\,d$$

The value of t just found is that of maximum chip thickness, and the theory further propounds that the maximum chip area varies as the square of maximum chip thickness if the chip or grain is assumed to be approximately triangular in shape; therefore:

$$t^2 = \frac{v^2}{V^2N^2} \cdot \frac{R + r}{Rr}\,.\,d$$

Similarly, for internal grinding, we get

$$t^2 = \frac{v^2}{V^2N^2} \cdot \frac{R - r}{Rr} \cdot d$$

The foregoing theory will be sufficient for the grinding considered in this book, and, as will be seen, it covers most of the machines in that it refers to SURFACE, EXTERNAL, CYLINDRICAL, and INTERNAL GRINDING.

Surface Grinders

Of these there are two main types: (1) the ordinary reciprocating table, which in its action is very similar to the horizontal milling machine,

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FIG. 90—HORIZONTAL SURFACE GRINDER, 18 IN. × 6 IN.
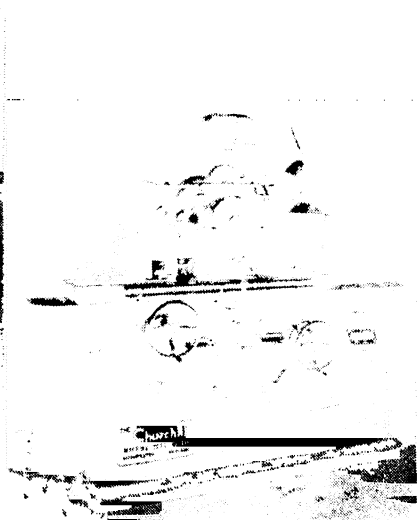
FIG. 91—10-IN HORIZONTAL SURFACE GRINDER

the general features of the machine being shown in Figs. 90 and 91, and (2) the rotary surface grinder, which has a revolving table and a vertical spindle and is not unlike a vertical milling machine.

The reciprocating table can be used in conjunction with a horizontal spindle, cylindrical wheel or disc wheel, and also with a vertical spindle (see Fig. 92), having either a cup wheel or a wheel built up of segments known as a segmental wheel. The vertical machine usually has a circular table, but there are cases in which the vertical spindle is used in conjunction with a reciprocating table, and vice versa where a circular table is used with a horizontal spindle and disc wheel, as shown in Fig. 93.

Cutting Speed.—The correct grinding-wheel speed is dependent on the arc of contact (see Fig. 97), together with, of course, the rigidity of

construction of the machine itself. The general figure for the peripheral speed of the grinding wheel for surface grinding is 4,000 ft. per minute and the wheel head is usually only provided with one speed. The 4,000 ft. per minute is regarded as a maximum, and in some cases efficient surface grinding is performed at 3,500 ft. per minute. The cylindrical wheel, running at constant r.p.m., has a variable surface speed, since the value of the surface or peripheral speed is dependent on the diameter, and as the wheel wears and is redressed the speed decreases. With vertical spindle machines having cup and segmental wheels, the speed does not vary and remains constant at 4,000 ft. per minute.

Work Speed.—In surface grinding the work has the same speed as the table on which it is mounted, whether reciprocating or circular, and

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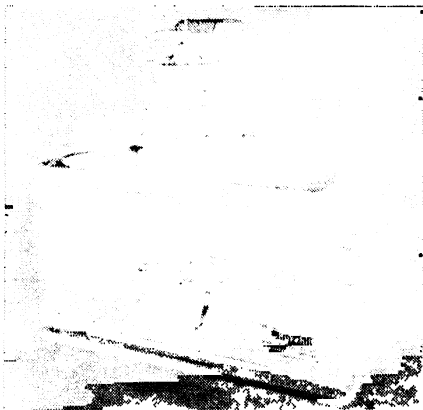


FIG. 92—SURFACE GRINDER VERTICAL SPINDLE, 30 IN.

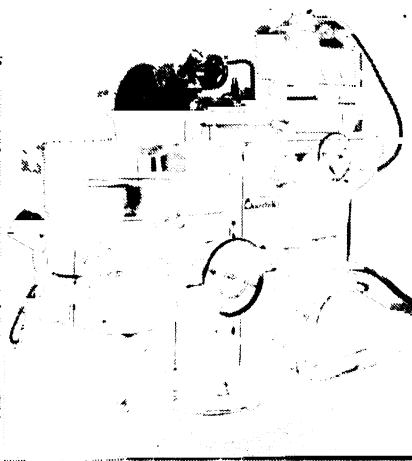



FIG. 93—RING AND SURFACE GRINDER, 24 IN.

it is therefore the table speed which determines the output. The work speed should be as high as possible, not only from an output point of view, but also from the consideration of the dissipation of the heat generated during the grinding. When the work speed is too slow, it will cause burning of the work and distortion due to the heat not being able to get away quickly.

Cylindrical Grinding

In connection with all machines, and no less with grinding machines, the question arises, " What are the factors which govern or control the machine output? " The main factors are, in the case of cylindrical grinding, rigidity of machine, accuracy required in product, grinding

wheel (size, shape, grade, and speed), table speed, work speed and cross feed, and also the question of lubricant. The rigidity of the spindle determines the wheel speed, and thus it happens that a light construction or imperfectly adjusted wheel spindle may require a speed of 6,000 ft. per minute, whereas the same wheel, or a softer-grade wheel of the same dimensions, will perform the work at a speed of say 4,500–5,000 ft. per minute and with better results. The legal limit of 6,000 ft. per minute may have contributed to the fact that at one time grinding-wheel spindles were often arranged to operate at a speed of approximately this figure of 6,000 ft. per minute, but in consequence of improved design and construction and the care and attention paid to bearings, etc., the best average speed is found to be about 5,000 ft. per minute for external grinding, and for large-diameter work, such as steel mill rolls, a lower figure of 3,500–4,000 ft. per minute is often used.

The grade of wheel plays an important part in the production programme, and where a machine is set to operate on one type or class of component, the correct grade and type of wheel can be used. If the work is in small batches and has to cater for a wide range of work, a wheel for general-purpose work will probably be used. In all cases it is better to choose a wheel that is too soft than one that is too hard.

Wheel Width

Mention of wheel width has already been made in connection with the computation of grinding times, and this factor also has a decided effect on output. To utilise a wide face wheel to its maximum capacity, the table travel must also correspond, and the two factors, table travel and wheel width, must be considered together as complementary conditions. A wide wheel and slow table traverse is uneconomical, and wasteful in so far as uneven wear of the wheel would probably result and the face of the wheel becomes round. If the traverse of the work per revolution is less than half the wheel width, then the cutting face of the wheel will gradually wear convex. If the traverse of the work per revolution is more than half the width of the wheel, then the cutting face of the wheel will remain flat. The best condition, one might truthfully say the ideal, is when the traverse per revolution of the work is two-thirds the width of the wheel. In any case it should not be less than half except for finishing. This condition has an important effect in determining values of table travel when wide wheels are being used, and because of this, grinding machines are made with table speeds of 16 ft. per minute and upwards. Thus production is obtained by a combination of high table speeds and wide face wheels. The points are illustrated in Fig. 94.

Work Speed

This does not play as important a part as the other factors, and it matters little whether the work speed be 30 ft. per minute or 60 ft. per

minute, save that the lower figure limits the table travel and indirectly affects the output. Even this, in some cases, can be offset by increasing

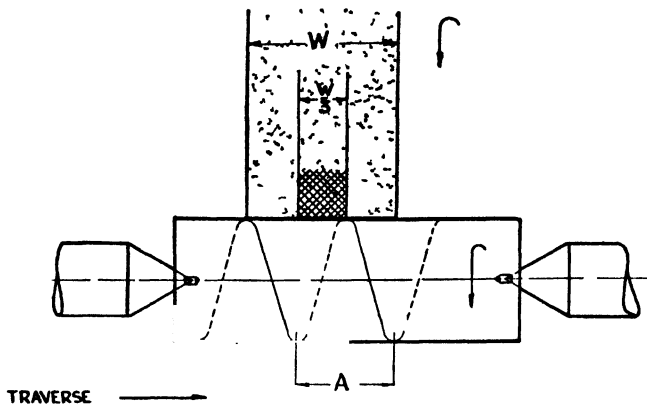
A = TRAVERSE PER REV OF WORK = $\frac{2}{3}$ WIDTH OF WHEEL.
MAX WHEEL WEAR CONCENTRATED ON SHADED PORTION

A = TRAVERSE PER REV OF WORK = $\frac{1}{3}$ WIDTH OF WHEEL
MAX WHEEL WEAR CONCENTRATED ON SHADED PORTION

Fig 94

the cross feed proportionately, in this case the cross feed would have to be doubled

Messrs. Churchill Machine Tools Ltd. recommend an average surface speed of 60 ft. per minute, based on experience.

Cross Feed

The cross feed given to a grinding wheel should operate at each reversal of the table, i.e. at the end of each stroke, and not at any other place, or at one end of the stroke only.

This method of cross feed is necessary in order to distribute the work over the whole width of the grinding wheel. Cross feed does not govern the amount of production or work output of the machine, as other factors do. The correct procedure is as already outlined ; obtain as fast a table travel as possible, giving a traverse of two-thirds the width of the wheel per revolution of the work at approximately 60 ft. per minute surface speed, and then give as much cross feed as the work, the machine, or the grinding wheel will stand. This should be from 0·0005 to 0·0015 in. on the work diameter at each reversal of the table.

Under these conditions, a machine with a fast table travel will give maximum output with a comparatively light cross feed, as compared with a machine having only a slow table travel, and, moreover, will not stress the work as highly. The wheel will, in these conditions, remove more material for a given wheel wear, and at the same time the machine will be more economical in power.

For grinding of this kind, i.e. for all external grinding operations, an ample supply of water should be provided without force. For a 14-in. diameter wheel between 5 and 10 gal. per minute should be used, and on larger wheels 20 gal. and in some cases up to 50 gal. per minute.

Form or Plunge Cut Grinding

In this class of grinding the table is stationary, the form or plunge cut feed feeding directly on to the work with the table stationary. This method may be applied within limits to either external or internal grinding, and grinding machines, either external or internal, can be arranged for plunge cut automatic feed with the table stationary or having a slight reciprocating motion. In some cases where it is preferred, the grinding-wheel spindle can be arranged with a slight axial float or oscillating motion. The object of such motion as this, applied either to table or spindle, is to help to preserve accuracy of the wheel cutting face, and to give a higher

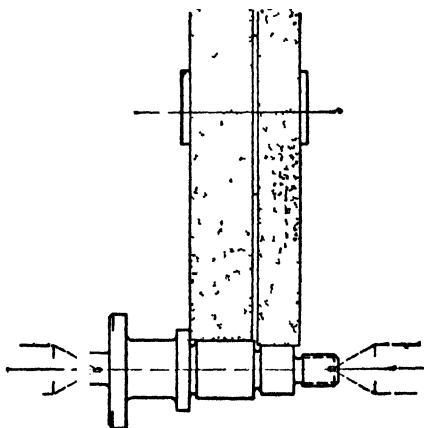



FIG. 95—FORM GRINDING

finish to the work surface by eliminating any possible minute grooves caused by faulty wheel truing.

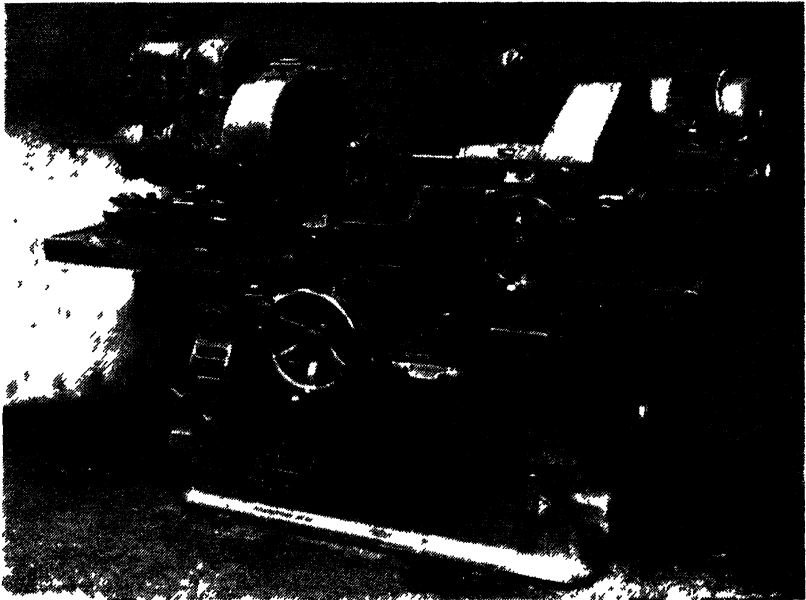
This kind of grinding requires a more rigid machine if wide forms or wide wheels are to be used, but any grinding machine may be used for plunge cut grinding up to the full width of the standard wheel for which the particular machine has been designed and built. The horse-power required for grinding, i.e. plunge cut or form grinding, increases proportionally to the increase in wheel width. An example of form grinding using two wheels is shown in Fig. 95.

Courtesy Churchill Machine Tool Co Ltd.

FIG. 96—10-IN. INTERNAL GRINDING MACHINE

Internal or Bore Grinding

The factors governing internal grinding are very similar to those for external grinding. There are many methods and types of machines used for bore grinding, including centreless machines, but these will be dealt with separately. In this section we will consider the plain internal grinding machine, the sizematic and the gagematic.

The plain internal grinding machine is an adequate machine for general work covering runs for small quantities where variations in hole size and lengths are encountered. The sizing of the work is hand controlled, the cross-feed screw being operated to a dead stop. In some cases the work is bored and faced at one setting, so that the holes are bored and end

faces finished at the one setting, an important point in such instances where the ground faces form a datum or reference face for subsequent

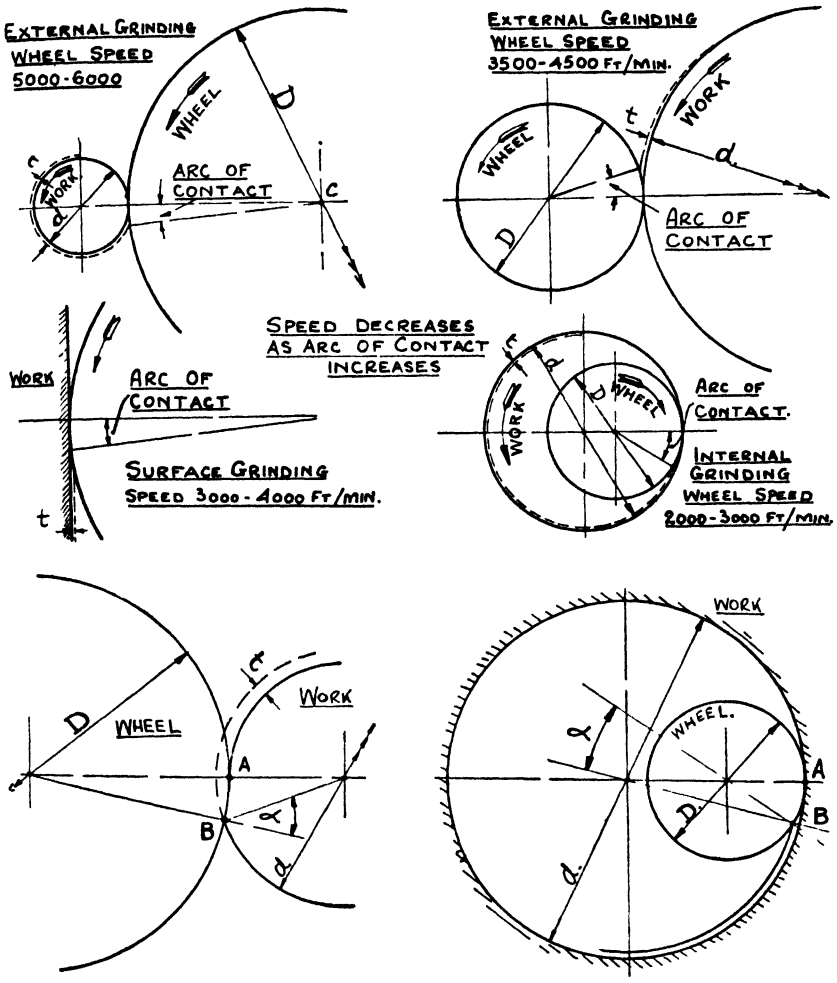



Fig. 97—Arc of Contact and Grinding Speeds

operations. Fig. 96 shows a typical internal grinding machine, Churchill 10 in.

Where the holes to be ground are of comparatively short length in relation to their diameter, plunge cut grinding can be employed, and is eminently suitable for this type of work. Here the wheel is longer than the work, and any table movement must be such that the oscillation of the

table allows full-length contact of the wheel and work at all times. Where the bores are longer than those which can be dealt with by plunge cut methods, the traverse-type machine must be used.

The efficiency of grinding is now known to be a function of rigidity as well as speed, and Messrs. Churchill suggest that, given suitable rigidity of grinding-wheel spindle, the wheel speed for maximum efficiency for internal grinding should be between 2,500 and 3,500 ft. per minute (see Fig. 97).

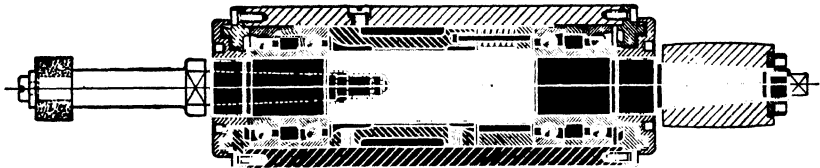
By using the speeds just given, a much heavier and therefore more robust and rigid internal spindle can be used with a resultant greater degree of accuracy. The application of these facts to actual practice has resulted in the machine makers, in conjunction and collaboration with the ball- and roller-bearings manufacturers, providing internal

Courtesy Churchill Machine Tool Co. Ltd.

FIG. 98—INTERNAL GRINDING SPINDLE, BARREL TYPE

grinding spindles with anti-friction bearings capable of producing high-precision work. Such a spindle is shown in Fig. 98.

Work Speed

The work speed, as in external grinding, has only an indirect effect on the output. It can be varied considerably both above and below the speed which is determined as giving the best conditions for the work in hand, and would have but little effect on the machine output. It might, however, affect the surface finish on the parts produced. Too slow a surface speed will, as is obvious, slow down the rate of production.

A work surface speed of 100–120 ft. per minute is taken as a basis, and modifications made above or below as circumstances demand.

Cross Feed

Again, automatic cross feed is immaterial in internal grinding unless the operation starts with a heavy cut and gradually diminishes as the finished size is reached, and any spring in the spindle is relieved.

On plain internal grinders operating on general work the use of automatic feed advancing the grinding wheel in regular increments would be too slow. The recommended method is to force the cutting as much as possible in the early stages, i.e. at the beginning of cut, and when near to the desired size to withdraw the wheel from contact with the work

momentarily, then advance it again to contact the work lightly for the finishing or sizing cuts. This relieves the spring of the grinding spindle, and results in the production of truly round and parallel holes.

Automatic Internal Grinding—Plunge-cut Method

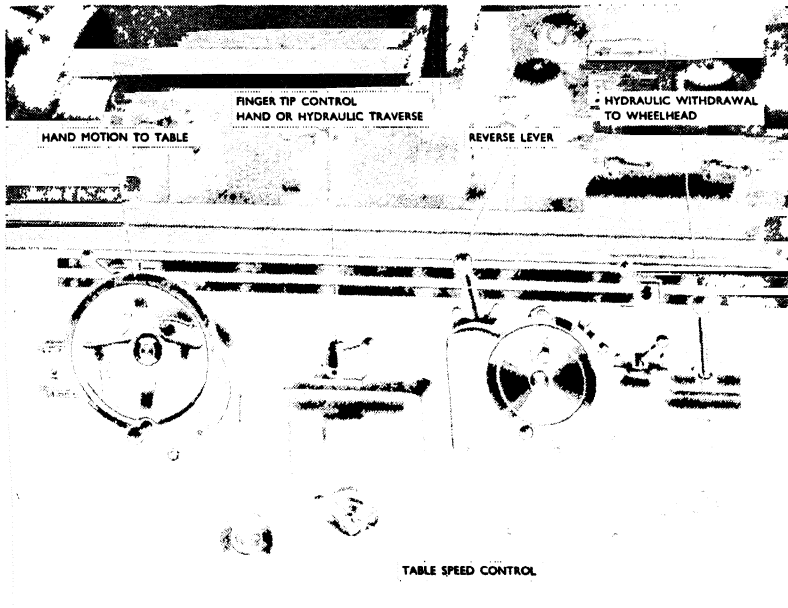
With machines of this type the cross feed of the wheel is effected by a cam which, operating on a mechanically timed cycle, feeds the wheel on to the work, commencing at a maximum which gradually diminishes to zero, then after sufficient dwell to build up or give a good finish to the

Courtesy Churchill Machine Tool Co Ltd

FIG 99—CONTROLS OF HYDRAULIC PLAIN GRINDING MACHINE WITH DIMINISHING FEED TO WHEELHEAD

work, causes the wheel to fall back at the completion of one cam revolution. The operation is represented diagrammatically in Figs. 100 and 101, the latter showing the grinding cycle for automatic machines.

The duration of the cam cycle can be varied to suit the cutting capacity of the wheel for any particular job. Thus, with a maximum of the wheel in engagement with the work, and the period of cam cycle which is a minimum to suit the nature of the wheel and work, the highest possible production rate is obtained with the highest degree of finish.

The finished size of the work is controlled by the position of the wheel-

truing diamond, which trues the wheel before it passes into the bore of the work, and with the known advance of the cam, a definite amount of metal removal resulting from a clean free-cutting wheel assures a bore finished to the very fine limits called for by present-day production requirements.

Cylinder Grinding

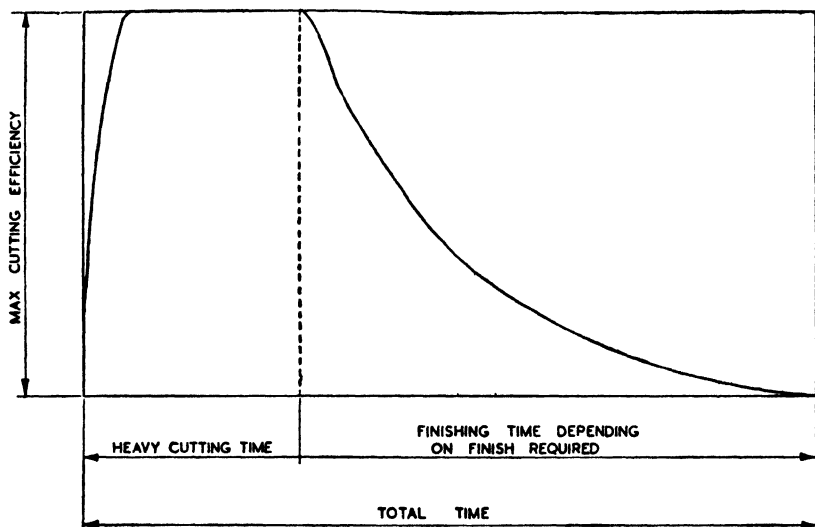
This is a method of internal grinding in which the work is stationary and the grinding wheel has a planetary motion whilst at the same time rotating at a high speed on its own axis. The grinding spindle is adjust-

Courtesy Churchill Machine Tool Co Ltd.

FIG. 100—TIME REQUIRED FOR GRINDING OPERATION

able during the grinding operation, and this type of machine is extensively used for external combustion engine cylinders, such as steam engine, locomotive cylinders, hydraulic cylinders, and pump bores.

This type of machine can be said to belong to the generative type, since the grinding wheel with its two motions generates the alignments of relative parts automatically. For example, two cylinders or similar parts, such as the tailstock and workhead of a plain grinding machine, can be ground in alignment with each other by bedding the bases of the two parts on the machine table and grinding the bores at the same time. If they were machined singly on another type of machine, the beds may need scraping in order to obtain the necessary alignment in assembly of the machine.

Arc of Contact.—Referring to Fig. 97 which shows the relative *positions of work and grinding wheel for the various methods of* grinding :

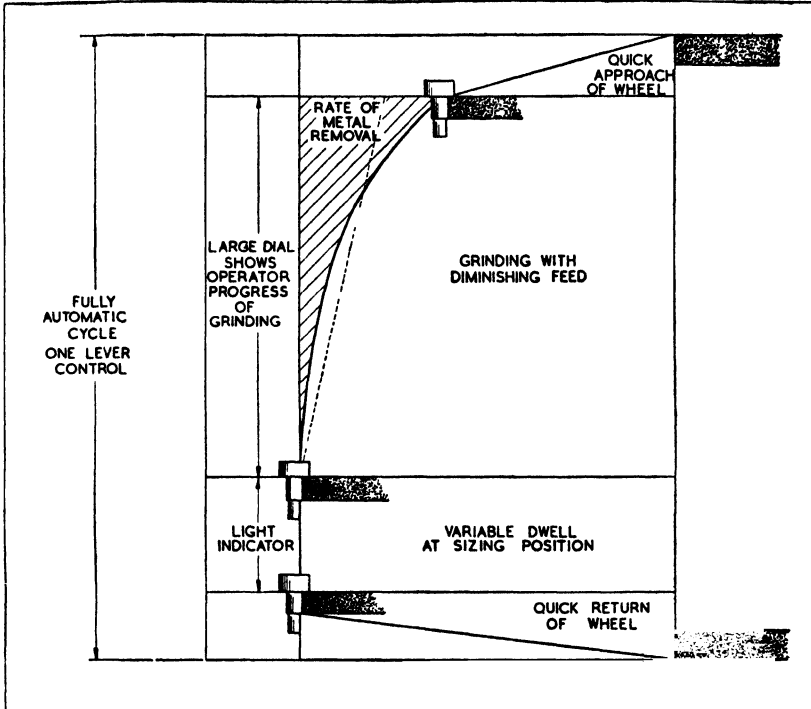
D = Wheel diameter,
d = Work diameter,
AB = Arc of contact,
t = Depth of cut.

Courtesy Churchill Machine Tool Co. Ltd.

Fig. 101—Grinding Cycle for Automatic Machines

The arc of contact AB is given as follows :

For external grinding :

$$AB = \sqrt{\frac{D \cdot d \cdot t}{D + d}}$$

For internal grinding :

$$AB = \sqrt{\frac{D \cdot d \cdot t}{D - d}}$$

The angle a is given by:

$$a = \sqrt{\frac{d + D}{dD}} \cdot t \quad \text{(external grinding)}$$

$$a = \sqrt{\frac{D - d}{dD}} \cdot t \quad \text{(internal grinding)}$$

Courtesy Churchill Machine Tool Co. Ltd.

Fig. 102—Internal Cylinder Grinding Machine, No. 2A

The Sizematic Grinding Machine

A well-known machine working on the "Sizematic" principle is the Heald, in which the sizing is incorporated and controlled by the cross slide and the wheel-truing diamond unit. The machine being automatic, simple, and easy to set up is therefore available for grinding small lots of work, and has thus a wide range of application. It may be used as an automatic or plain internal grinder. The automatic feature is applied to every operation in the grinding cycle except loading and operating the starting lever. This feature includes a rapid table approach up to the work, followed by a slow-down to roughing speed with the grinding wheel cutting at roughing feed. The grinding operation continues until the hole is very near to finish size, when the wheel is withdrawn from the work, the diamond drops into position, the wheel trued or dressed at

correct speed, and the wheel then returned to complete the grinding at finishing speed and feed.

When the hole has reached finish size, the wheel automatically withdraws from the work at high speed, the operator " backs off " the wheel, and all units go to the rest position. The work is removed and the cycle is complete.

The table of this machine moves on flat and vee ways (see Chapter VI), and the table speeds are variable and the changes from roughing speed, truing speed, and finishing speed are performed automatically. The roughing speeds are adjustable from 0 to 32 ft. per minute.

Cross Slide.—This is arranged with coarse feed to the wheel when rough grinding, which changes at a predetermined point to finishing feed automatically. The sizing unit which controls the various movements after the work has been placed in the chuck is located on the cross slide, and it consists mainly of a cam and two contact points. The first permits the current from a generator on the back of the machine to energise a magnet in the magnet box on the front, thus operating a lever which lifts the latch on the centre dog, causing the stroke of the table to be amplified for the wheel-dressing operation. The second contact energises a second magnet that operates another lever, which in turn lifts both dog latches, allowing the table to go to the rest position as the work is ground to size.

There is also incorporated in the cross slide an arrangement which automatically advances it sufficiently to compensate for wheel wear. This ensures that a slight amount of stock will be removed from the wheel each time the diamond is dropped into position (see Fig. 103).

Gagematic Internal Grinding Machine

This machine is very similar in construction to the sizematic machine just dealt with, but has one outstanding feature which distinguishes it from this and other machines. This distinction lies in the provision of an automatic gauging fixture or device by means of which the machine produces work to very close limits and the parts are automatically gauged by a rough and finish gauge during the grinding operation. The device consists essentially of solid gauges which are presented automatically at split-second intervals to test the size of the hole being ground.

The operation of the grinding cycle is fully automatic, as in the sizematic machine, i.e. the table approaches the work with a fast speed, slows to roughing speed, and wheel then cuts with a roughing feed.

The sizing mechanism consists of a set of gauges (see Fig. 104), one a roughing and the other a finishing gauge. These are usually made integral and mounted on a gauge rod, which extends through the work spindle. The rod is concentric with and keyed to the spindle ; thus the gauges rotate with the work and are therefore only subjected to slight wear. The gauges come into operation when the workhead starts

revolving and the grinding wheel starts reciprocating backwards and forwards in the hole.

As the main table carrying the wheelhead moves to the left, the end of the table *C* presses against the screw *D*, moving the gauge push rods *G* back against a spring and at the same time rod *B* and the gauges *A* are pushed away from the hole. This permits the wheel to pass through the back of the hole without striking the gauges. As the wheel returns and clears the work on the outward stroke, the gauge is brought forward and at-

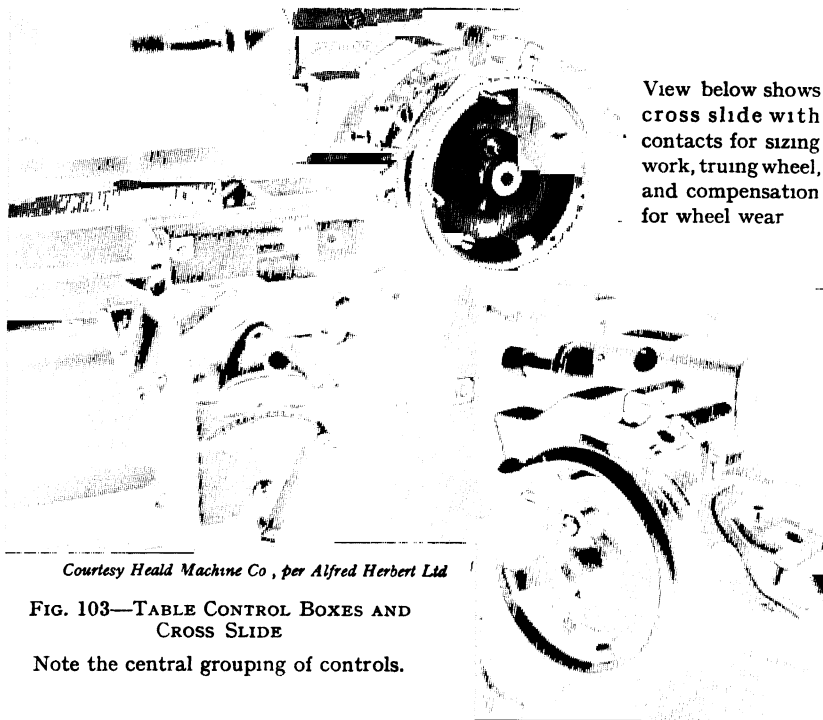
View below shows cross slide with contacts for sizing work, truing wheel, and compensation for wheel wear

Courtesy Heald Machine Co, per Alfred Herbert Ltd

FIG. 103—TABLE CONTROL BOXES AND CROSS SLIDE

Note the central grouping of controls.

tempts to enter the hole. The wheel continues to remove stock under the roughing feed until the first or roughing gauge enters the hole and the gauge rod moves forward until the finishing gauge makes contact with the work. This extra movement of the gauge rod permits contact to be made at points *EE* which are opposite and at the back of the points *E*, as shown in Fig 104. This contact closes an electric circuit which energise magnets and cause the table to short stroke automatically, the diamond to drop into position, and the wheel to be dressed.

The wheel now re-enters the work and finish grinds at finishing feed. With each stroke the finish gauge attempts to enter the hole, and when the work is finished to the exact size, the gauge does enter, causing the

contacts at E to close another electric circuit, thereby returning the table to the rest position.

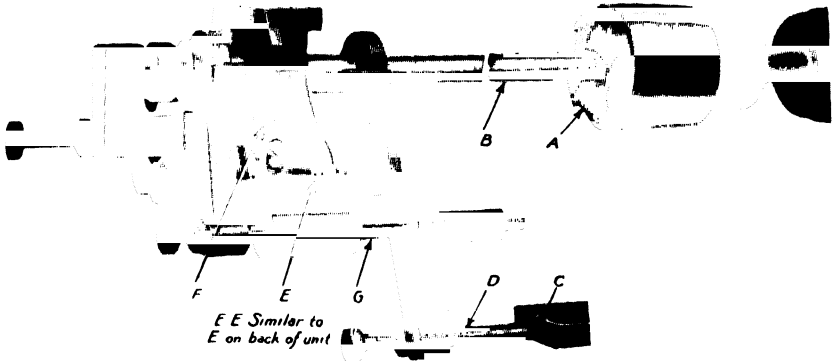
After the gauges have entered and sized the work, oil pressure in the

Courtesy Heald Machine Co., per Alfred Herbert Ltd.

FIG. 104—HEALD GAGEMATIC MECHANISM

cylinder F automatically retracts the gauges from the work, allowing this to be removed and another piece to be placed in the chuck.

Centreless Grinding

This method, as its name implies, is the grinding of work without holding it between centres or on a mandrel between centres. The principle

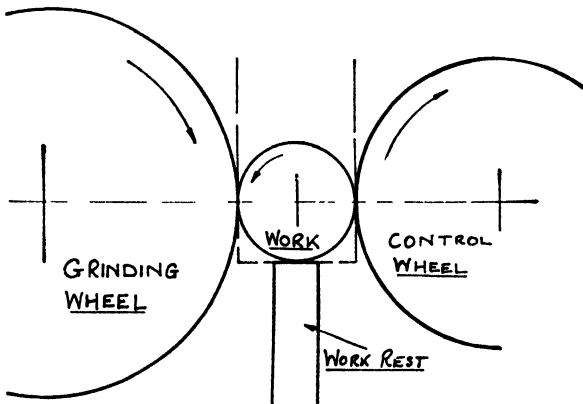



FIG. 105

of centreless grinding involves the following elements (see Fig. 105):

1. Grinding wheel.
2. Control or regulating wheel.
3. Work rest.

The grinding wheel is similar to those used in orthodox grinding machines, and the control wheel is similar to the grinding wheel but can be inclined to give the feed of work through the machine.

The work rest incorporates suitable guides for leading the work into the wheels for grinding and receiving it from them and guiding it away after the operation. It also has one and sometimes two work blades for supporting the work during the cut.

All the above elements may be arranged in a number of ways, depending on the design of the machine, but the underlying principle is the same in each case.

In the ordinary grinder, where work is ground on centres, mandrel, or in a chuck, the revolving of the work, the wheel, and the traverse of wheel

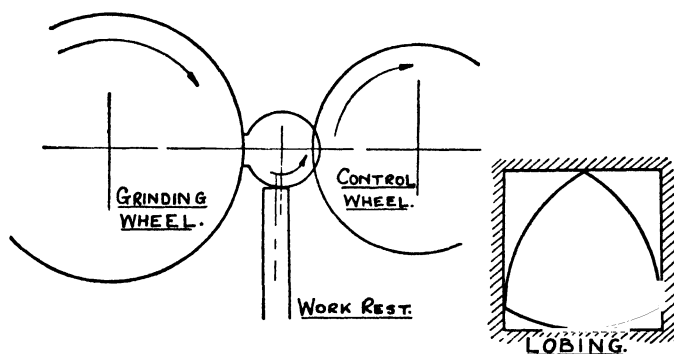



FIG. 106

produce or generate a cylinder, but in the case of the centreless machine, there are no centres, and apparently no means of controlling the roundness of the work. Referring to Fig. 105, it will be seen that the cutting pressure developed by the grinding action forces the work down against the work-rest blade and also against the control or regulating wheel, which is made of a rubber-bonded abrasive. It is similar to the actual grinding wheel apart from the bond, and it provides a continual friction driving force, rotating the work at the same peripheral speed as itself, and advancing it along at the same time.

It will be clear that the ground portion of the work is determined by the distance between the two moving surfaces of the wheels, but it must also be remembered that a piece of constant diameter is not necessarily a circular piece. A piece may give a constant-diameter reading either by micrometer, snap gauge or calliper, but yet not be a perfect cylinder due to lobing. The condition is shown in Fig. 106, as is the arrangement of the work and blade and wheels in a case producing a lobing condition. In Fig. 105 it will be seen that the work, grinding wheel, and control wheel are on the same centre line, and the points of contact of wheels with the work and blade with the work form three sides of a square. Thus,

a high spot on the work coming into contact with grinding or control wheel will produce a corresponding concave spot diametrically opposite. Grinding work under these circumstances will produce work as shown in Fig. 106 which, whilst being of constant diameter, is not cylindrical.

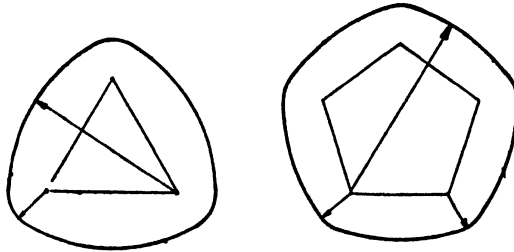



FIG. 107

The extreme case shown is a three-arc triangle, and other possible cases of lobing are shown in Fig. 107.

To combat this lobing, the centre of the workpiece is elevated above the centres of the wheels by raising the work rest. If now a high spot on the work comes into contact with the control wheel, it will cause a low spot at the grinding wheel, but not diametrically opposite. As the workpiece is rotated, the high and low spots will not come opposite each other, and so the rounding effect desired is gradually attained.

To obtain a maximum corrective rounding action, the work rest has a blade with an angular top, as shown in Fig. 108, and this produces a dis-

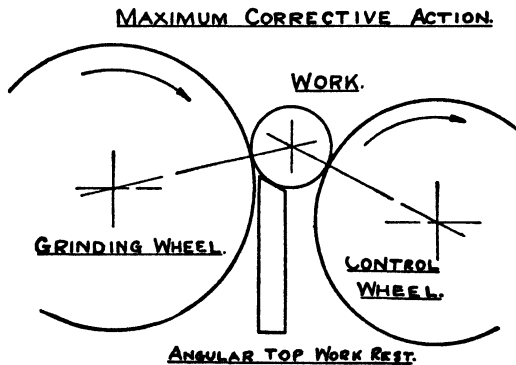



FIG. 108

tinct corrective action. This corrective action is shown in Fig. 109, from which it will be seen that two lines *A*—*A* and *B*—*B* are drawn tangentially at points where the work makes contact with the wheels, and another line *C*—*C* where the angular top blade contacts the work. If a low spot on the work comes into contact with either the work rest or control wheel as shown by the dotted outline of the work, the centre will be lowered.

The centres of the wheels are fixed, and the smallest diameter of work that can be generated is obviously on their centre line, i.e. on a line joining their centres. Thus, the lowering of the work centre towards this centre line of the wheels causes a reduction in the diameter of the work. Conversely, the heightening of the work centre produces a larger diameter workpiece. Thus the grinding wheel, instead of leaving a high spot on the periphery of the work equal to the concave portion at the point of contact with the control wheel, generates a proportionally smaller high spot at its contact with the work. In this way the high and low spots cancel or damp themselves out theoretically, and in actual practice a cylindrical form is generated in a short time.

The higher the work centre above the wheel centres, the quicker is the rounding action, the limit being governed by the lifting of the work due

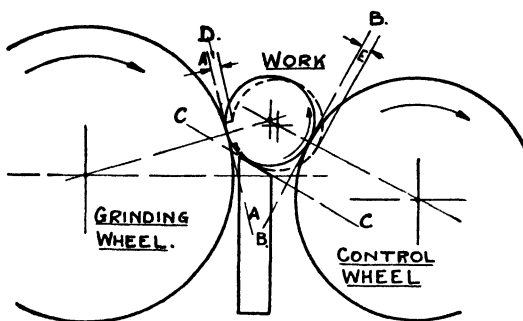



FIG. 109

to the increased vertical component of the forces acting which, when this is large enough, lifts the work from the blade and wheels.

The speed of the grinding wheels is usually between 5,400 ft. per minute and 6,000 ft. per minute, and the surface speed of the control wheel varies between 50 and 200 ft. per minute depending on the feed required.

Methods of Centreless Grinding

There are four principal methods of Centreless Grinding:

1. Through feed.
2. Infeed.
3. Endfeed.
4. Concentric.

These are governed by the nature of the work being ground.

1. Through Feed.—This type of centreless grinding is usually confined to parallel work such as bars, i.e. straight cylindrical work such as pistons, rollers, gudgeon pins and ballraces. The method employed is to pass the work between the grinding and control wheels, the grinding

being accomplished as the work passes from one side of the wheels to the other.

The feed, i.e. axial movement of the work past the grinding wheel, is imparted by the control wheel, which is swivelled round to give the amount of feed required. The control wheel can be swivelled about a horizontal axis from zero to about 7° or 10° maximum relative to the axis of the grinding-wheel spindle. The amount of feed is governed by the control-

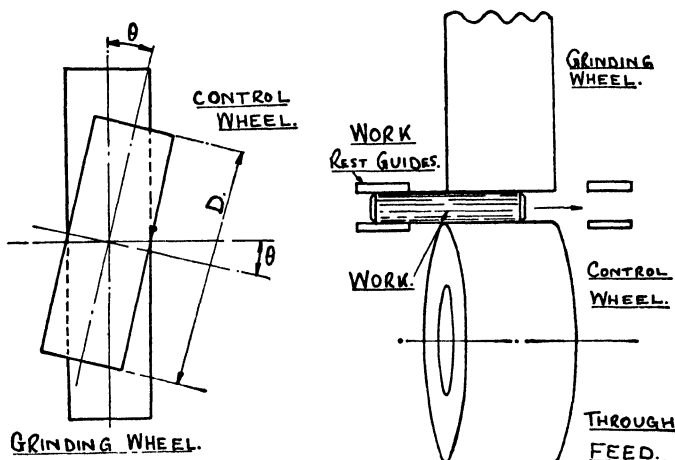



FIG. 110

wheel diameter, its speed and its inclination, and the amount of feed is given very approximately by

$$F = \pi DN \sin \theta$$

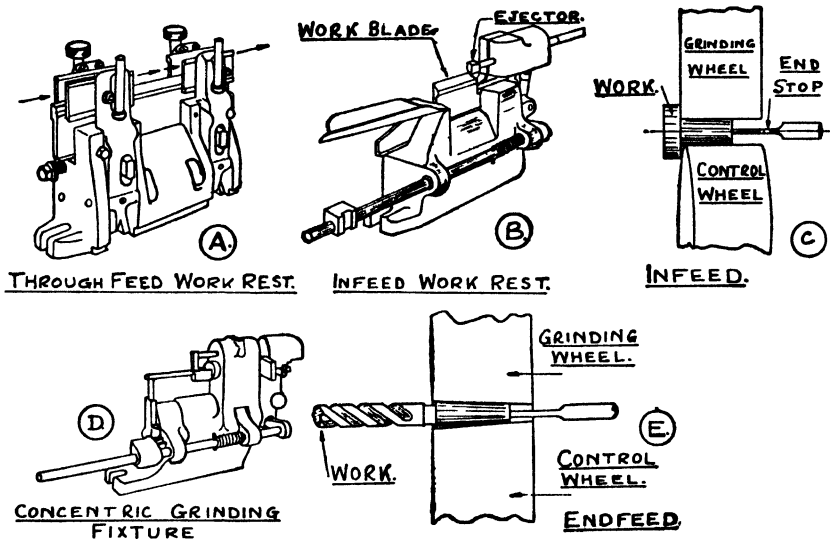
where F = Feed of work in inches per minute.
D = Control-wheel diameter in inches.
N = Speed of control wheel in revolutions per minute.
θ = Angle of inclination of the control wheel in degrees.
(See Fig. 110.)

The above gives the theoretical feed rate, but, of course, there may be slip between work and wheels, and the actual feed will then be less than the figure given by the above expression. This amount of slip is small, however, and usually is not more than 2 per cent.

Example.—What feed in inches per minute will be obtained by inclining a control wheel 12 in. diameter 6° if it makes 70 r.p.m.?

$$F = \pi DN \sin \theta$$
$$= \pi \times 12 \times 70 \times \sin 6°$$
$$F = 12\pi \times 70 \times 0{\cdot}1045$$
$$F = 87{\cdot}78\pi$$
$$F = 276 \text{ in. per minute}$$
$$\therefore F = \textbf{23 ft. per minute.}$$

The arrangement of the set-up for through feed is shown diagramatically in Fig. 110.

In special cases through feed can be applied to other than parallel work. Tapered work which is comparatively short in length can be carried across the face of the grinding wheel by using a special work-holding fixture or work roll. The roll has a groove cut in its periphery in the form of a slow spiral, and the work is thus fed across the grinding wheel by this groove, which it enters at one end in the unground state and leaves it at the other after being ground. The groove is so arranged

Figs. 111 to 114

that the face of the work to be ground is parallel to the face of the grinding wheel.

2. Infeed.—This method corresponds to plunge-cut or form grinding on the cylindrical grinding machine. It is usually used when the work to be ground has a shoulder, head, or some other projecting portion which prevents the passage of the piece through the wheels. This method is also used for the simultaneous grinding of work with several different diameters, and for work having an irregular profile. Since in this case there is no need to feed the work past the grinding wheel, the control wheel is only slightly tilted in order to keep the work held against the end stop. In other cases the control wheel has no tilt or inclination at all, but is in alignment with the grinding wheel. The set-up for infeed grinding is shown in Fig. 112.

3. Endfeed.—This method is used mainly for tapered work, a good example being the grinding of twist-drill shanks, i.e. the Morse taper

portion. In this instance the grinding wheel, control wheel and work rest are set in fixed relationship to each other, and the work then fed in. For such taper work either the grinding wheel or control wheel or both can be dressed to give the amount of taper required. An example of end-feed grinding is shown in Fig. 113.

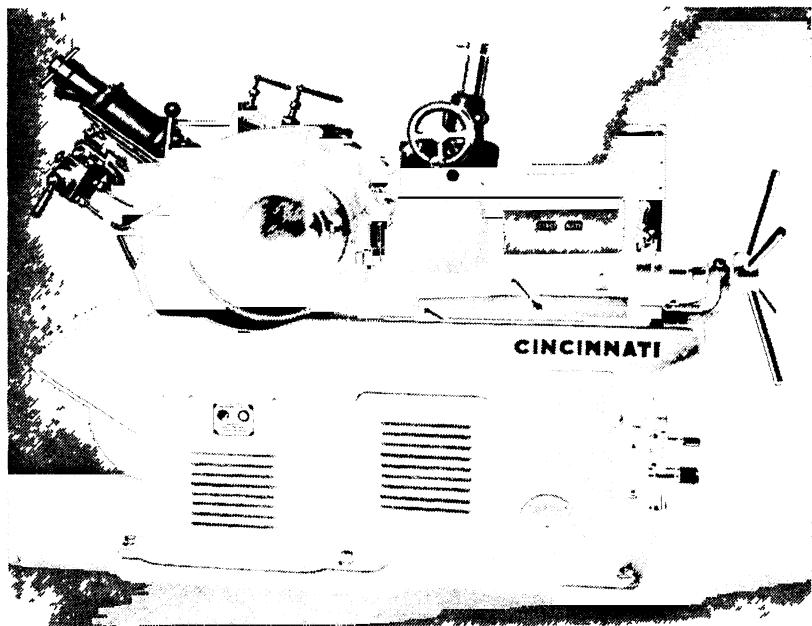
4. Concentric Feed.—Concentric grinding enables the outer cylindrical surfaces of work to be ground concentric with previously ground or machined bores. It may be regarded as a variation of the infeed method, but in this case the work is supported, not by an angular top blade in the

Courtesy Cincinnati Milling Machines Ltd

Fig. 115—Centreless Grinding Machine

work rest, but is mounted on an arbor. The arbor with the work mounted on it is free to float in a horizontal plane to and from the grinding-wheel surface. A typical set-up for concentric grinding is shown in Fig. 114.

A general view of a centreless grinding machine is shown in Fig. 115.

Internal Centreless Grinding

So far the centreless grinding considered has all been external. Now we consider the internal centreless grinding methods. The grinding cycle for this can be fully automatic—the parts fed by chute from a hopper to the grinding wheel and support wheel and then automatically ejected when finished and led to a workbin or stand. Moreover, the bores can be ground either parallel or taper.

The Heald No. 81 Centreless Internal Grinding Machine has a fully automatic cycle, and can be worked on either their gagematic or size-matic principle, details of which have already been discussed earlier in this chapter.

The automatic loading cycle is as follows, but first let it be explained that there are two supporting rolls, or rather one support roll or wheel

Courtesy Heald Machine Co, per Alfred Herbert Ltd.

FIG. 116—HEALD CENTRELESS INTERNAL GRINDING MACHINE

and one pressure roll, and a regulating or control wheel contacting the outer surface of the work, the general arrangement of which is as shown in Fig. 116.

Most work is hopper fed to this type of machine, and as a workpiece falls by gravity, it comes up against the support roll. The pressure roll now moves forward and holds the piece in position and the bore is ground by either the gagematic or sizematic cycle. When the piece is finished, a work ejector, or loading arm as it is called, moves upward and takes the finished part up with it, and it rolls away down a chute. As this loading arm moves upwards, the work stop holding the workpieces in check

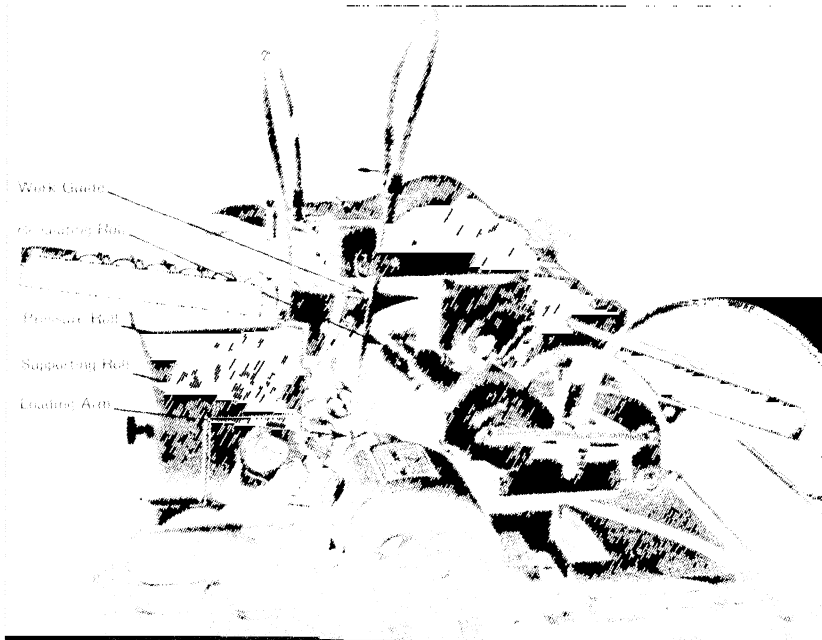
allows another unground piece to fall against the regulating roll and thence on to the loading arm, which it follows down until it comes to rest on the support roll. The loading arm continues and moves out of the way. The pressure roll comes forward and holds the piece, and the grinding wheel approaches at roughing feed, which it continues until a predetermined point is reached, then finishes at finishing feed, after which the

Courtesy Heald Machine Co., per Alfred Herbert Ltd

FIG. 117—SHOWING HOW WORK IS HELD BETWEEN THREE ROLLS AND REVOLVES ON ITS OWN OUTER SURFACE

loading arm starts its upward travel, the pressure roll is drawn back, and the work ejected, and so the grinding cycle continues.

Thread Grinding

Grinding is applied to many operations, and nowadays many threads are produced by thread grinding. Precision threads for instrument work, etc., are produced economically by this method. In these machines the principle employed is that of using a formed grinding wheel, which is provided on its periphery with an accurate form of the thread to be produced by grinding. The thread grinding machine can produce threads on either hardened or soft work and, moreover, the rate of production is four to five times that of the automatic-type screw machine (Auto Lathe).

The grinding wheel can have but a single thread form, and produces

the thread in a manner similar to a single-point cutting tool, or it may have two or more thread forms. In some cases the whole face of the wheel has the thread formed on it, and the thread in this case is produced in a manner similar to plunge cut or form grinding. Thus we come to the main methods of thread grinding.

1. Traverse Grinding.—In this method of thread production the grinding wheel traverses or passes over the work; in some machines the work moves across the face of the grinding wheel. The first thread form on the grinding wheel removes the greater part of the metal, and the following threads on the wheel effect the finishing. It should be remembered that the grooves in the grinding wheel are annular ones, and the wheel is inclined to the helix angle of the thread being ground.

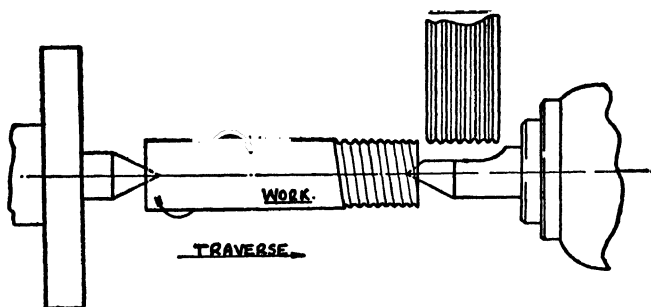



FIG. 118—TRAVERSE GRINDING

The figures shown in Fig. 118 will make the operation of thread grinding by traverse method clear.

2. Plunge-cut Grinding.—This method is generally employed on short-length threads, and is sometimes faster than traverse grinding; but as the wheel must be plunged into the work to the full depth of thread before the work has made one revolution, there is greater wheel wear. Due to this condition, the crest of the thread form is worn away or deformed quickly, and consequently the wheel needs more frequent dressing. The general layout for producing a thread by plunge-cut grinding is shown in Fig. 119, which clearly shows the relative positions of wheel and work. The length of thread on the wheel should be at least the actual length to be ground; that is, the thread length plus an allowance for the workpiece to make $1\frac{1}{4}$–$1\frac{1}{3}$ revolutions to complete the thread.

The grade of wheel is of paramount importance in thread grinding, and fine grades must be used; correct wheel dressing is even more essential than in other cases of grinding. Reference has already been made to wheel dressing and wheel-dressing fixtures which are incorporated in the design of the various grinding machines already discussed, and the thread grinder also has provision for re-forming the wheel when this becomes worn.

There are two methods mainly used:

1. Wheel Crushing

This uses a crushing roller of hardened steel, which is fed into the wheel to produce the required thread form ribs on the grinding wheel.

On the Churchill Thread Grinding Machines a " PULCRUSH " attach-

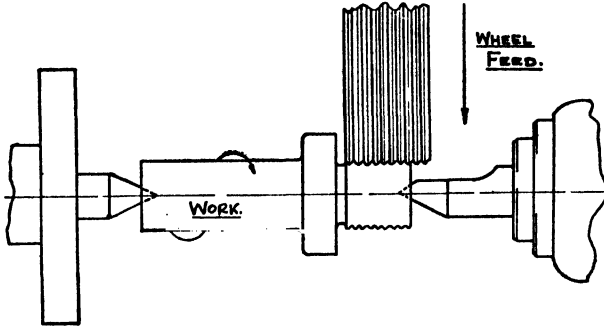



FIG. 119—PLUNGE-CUT GRINDING

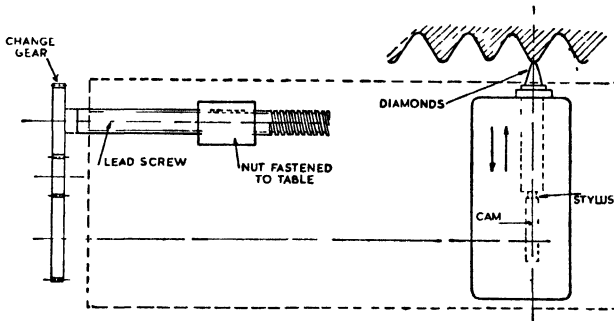
ment is built into the machine for wheel forming. It is mounted directly on the table in such a way that the crushing pressure is always in the same plane as the grinding pressure, and this, together with the design of the

Courtesy Coventry Gauge & Tool Co Ltd

FIG. 120—DRESSING THREAD GRINDING WHEEL BY DIAMOND

system, relieves the machine, and in particular the wheel-spindle bearings, of the excessive loads usually encountered with this form of wheel dressing.

The unit, together with the wheel, can be seen in Fig. **121**. It is preferable to incline the crusher to the helix angle of the thread when dressing the wheel.

2. Diamond Dressing

Wheels may be dressed by a diamond, which is actuated by a suitably designed cam for the movement normal to the wheel face and a precision screw for the traverse. The movement is similar to cutting a thread

with a single-point tool in the lathe, using the leadscrew and change wheels. Suitable change gears and the leadscrew in the dressing fixture provide the traverse for the diamond, giving correct movement for the pitch of thread on the grinding wheel, and the cam provides the inward movement. The combination of the two gives the diamond the required movement to produce the necessary thread form on the wheel (see Fig. 120).

Another method employs the pantograph which is arranged to follow

Courtesy Churchill Machine Tool Co Ltd.

FIG. 121—CRUSHING THREAD FORM ON GRINDING WHEEL : PULCRUSH METHOD

a profile of the desired thread form which is made to a large scale. The stylus or pointer follows the contour of the thread form, and via the mechanism and linkage of the pantograph reduces the contour to the actual size of thread form required on the grinding wheel.

Wheel Dressing

All grinding wheels need dressing, and for accurate work this is best performed by a diamond. As has already been indicated, the machines have wheel-dressing fixtures incorporated in the design, and can be applied to the wheel by hand or automatically.

As an instance of wheel dressing, let us consider the truing up of the control wheel of a centreless grinding machine. The standard equipment trues the wheel to a perfect cylinder, but if other shapes are de-

sired, a profile truing fixture must be used. The control wheel is trued by the diamond in such a way that the line of contact of the diamond with the wheel corresponds with the line of contact of the work with the wheel, in order to ensure that when the work is passing between the wheels it makes contact with the entire width of the wheel face. This condition is arrived at by considering the following points:

1. Inclination of the control wheel.
2. Angle of inclination of wheel-dressing slide.
3. Relationship of work centre with respect to wheel centre.

The first factor depends on the type of work and feed rate required, and the second factor is dependent on the first in so far as the truing

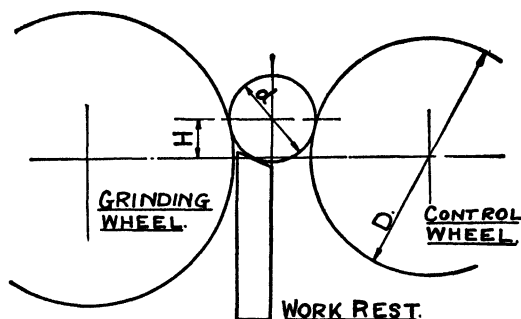



FIG. 122

fixture is swivelled round an angle equal to the angle of inclination of the control wheel. The third factor is determined by the work diameter, and the position of the work and fixture relative to the wheel can be seen in Figs. 122 and 123.

If D = Control wheel diameter,
d = Work diameter,
H = Distance between work centre and wheel centre,
S = Amount of set over of truing diamond.

Then $S = \frac{DH}{D + d}$

Fig. 123 shows the adjustment of the truing diamond, and it should be remembered that the highest speed of the control wheel should be used when dressing the wheel.

The elements which determine the amount of set over of the control-wheel truing or dressing diamond, S, shown in Fig. 122, are further shown in Fig. 123.

Tool and Cutter Grinder

This chapter on grinding and grinding machines would indeed be incomplete if no mention were made of the tool and cutter grinder which,

apart from its use in the commercial manufacture of small tools, is also found in every toolroom. The amount of material which is removed from the tools by the grinding wheel of this machine is usually small, the cuts being light, and in consequence the machines themselves are of a lighter construction than ordinary grinders. At the same time the tool and cutter grinder is a sturdy and rigid machine, and it might safely be said that its main work is the grinding of small tools, such as milling cutters, drills, reamers, etc.

In some instances, however, by fitting an internal grinding spindle and

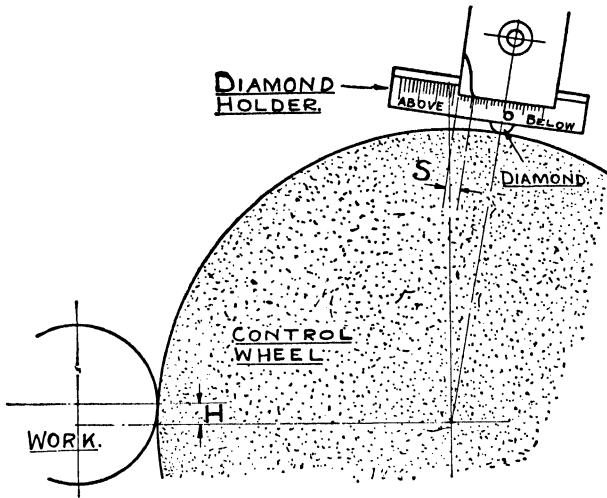



FIG. 123

a chuck to the workhead spindle, small cylindrical parts can be bored to precision limits.

Briefly, the main points of the tool and cutter grinder are the sliding table which, supported on a suitable base, reciprocates in the same manner as the table on cylindrical and surface grinders and milling machines. Mounted on this sliding table is a swivelling table, which can be turned through 180° in some machines. At the rear of the table is the wheel head, which can be swivelled round in a horizontal plane. On the swivel table the workhead is mounted at the left-hand end, and the tailstock with running centre at the other. The workhead can be rotated in two planes, horizontal and vertical, and with these adjustments the machine is of the Universal class.

Illustrations of typical tool and cutter grinding machines are shown in Figs. 124, 125, 126 and 127.

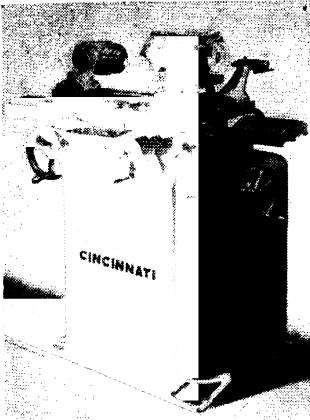
The work handled by the tool and cutter grinder is as already indicated, and, taking a milling cutter as an example of cutter-grinding, it is found

Courtesy Cincinnati Milling Machines.

FIG. 124—CINCINNATI TOOL AND CUTTER GRINDER

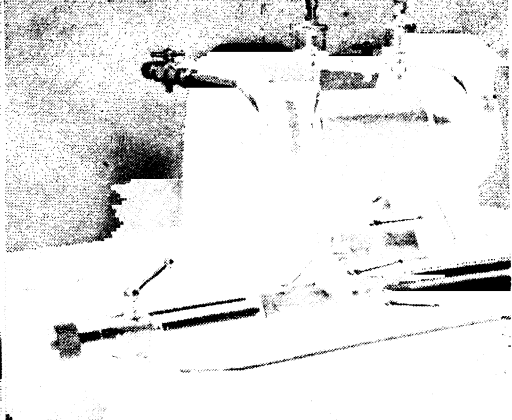



FIG. 125—GRINDING HEAD FOR OFF-HAND GRINDING SMALL TOOLS

Courtesy A. C. Wickman Ltd.

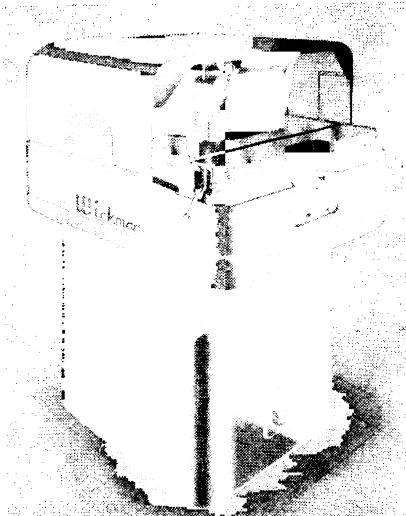
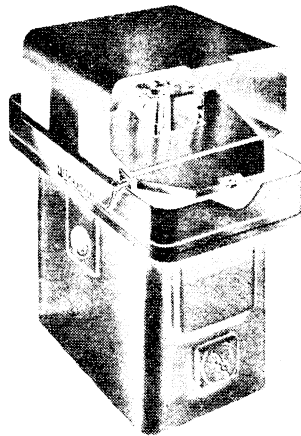



FIG. 126

FIG. 127

WICKMAN TOOL GRINDER, NEVEN DIAMOND WHEEL FOR LAPPING TUNGSTEN CARBIDE TIP TOOLS

Views show adjustable table which can be set to give required angles on cutting tools.

that in the case of new cutters the grinding consists of grinding the *land for cutting clearance.*

When a cutter has been *in use, it needs sharpening, and again the tool* and cutter grinder puts the cutting clearance on the cutter teeth at the time they are sharpened. This operation may be performed either:

(*a*) By using a disc or cylindrical wheel.
(*b*) By using a cup wheel.

These two methods are shown in Figs. 128 and 129, and referring to Fig. 128(A) the grinding of cutter teeth by using the periphery of a disc (cylindrical) wheel, it will be seen that the centre of the cutter is set below the wheel centre in order to obtain the amount of clearance required on the cutter. The radial line of the tooth edge when produced to the cutter centre is a horizontal line as shown.

Let R = Radius of grinding wheel.
r = Radius of cutter.
h = Height of offset of cutter tooth from wheel centre.
θ = Clearance angle.

Case **1.**

$$\frac{h}{R} = \sin\theta$$

$$\therefore \mathbf{h = R \sin \theta.}$$

Case **2.**

$$\frac{h}{r} = \sin\theta$$

$$\therefore \mathbf{h = r \sin \theta.}$$

Example.—A milling cutter $3\frac{1}{2}$ in. diameter is to have a clearance angle of 8°. Calculate the relative positions of wheel and cutter for:

(*a*) An 8-in. diameter disc wheel.
(*b*) Using face of a cup wheel.

(*a*)

$$\begin{aligned} h &= R \sin\theta \\ &= 4 \sin 8^\circ \\ &= 4 \times 0{\cdot}1392 \\ \therefore h &= \mathbf{0{\cdot}5568\ in.} \end{aligned}$$

That is to say, the cutter will be set 0·5568 in. below wheel centre as shown in Fig. 128(A).

(*b*)

$$\begin{aligned} h &= r \sin\theta \\ &= \tfrac{1}{2}\,(3\tfrac{1}{2} \sin 8^\circ) \\ &= 1{\cdot}75 \times 0{\cdot}1392 \\ \therefore h &= \mathbf{0{\cdot}2436\ in.} \end{aligned}$$

Thus, as shown in Fig. 129(A), the cutter tooth will be set 0·2436 in. *below the cutter centre.*

Here it should be noted that the position of the wheel centre is not

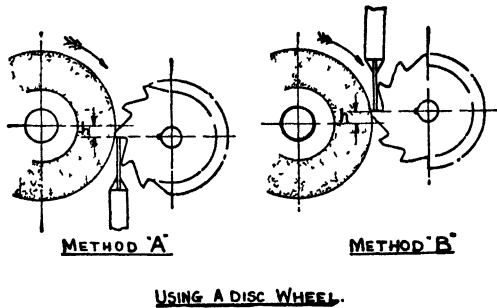



FIG. 128

important, but the cutter diameter is, and in Case (1) cutter diameter does not influence the setting for cutter sharpening, but the position of the wheel does.

Now, if the cutter has spiral teeth, the helix angle of the teeth affects

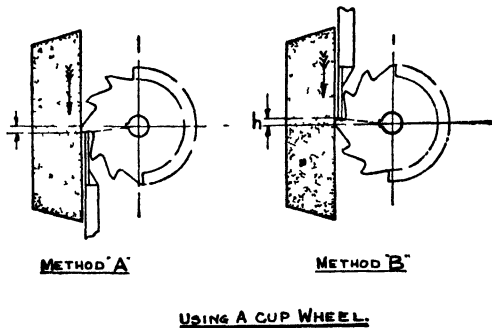



FIG. 129

the setting which is required to give the clearance angle θ normal to the tooth face, as this axial clearance angle for the setting differs from the normal clearance angle. The modification required will be understood by reference to Fig. 130.

Let θ_n = Normal clearance angle.

θ_a = Axial clearance angle.

a = Helix angle of spiral teeth on milling cutter.

Now referring to triangles (Fig. 130):

$$\tan \theta_a = \frac{GH}{DG} = \frac{EF}{DG}$$

$$\frac{DF}{DG} = \cos a$$

$$\therefore DG = \frac{DF}{\cos a}$$

Hence, $\tan \theta_a = \dfrac{EF}{DG} = \dfrac{EF}{\dfrac{DF}{\cos a}} = \dfrac{EF}{DF} \cos a$

Now $\dfrac{EF}{DF} = \tan \theta_n$

$$\therefore \tan \theta_a = \tan \theta_n \cos a$$

i.e. the tangent of the axial clearance angle θ_a equals the tangent of normal clearance angle θ_n times cosine of the helix angle of the teeth a.

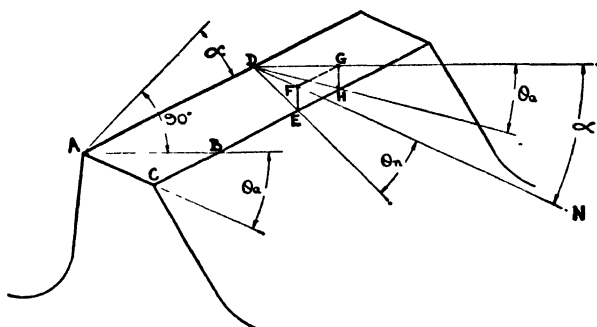



FIG. 130—ANGLES FOR CUTTER WITH HELICAL TEETH

Thus, due to the helix of the spiral teeth, the setting for obtaining a given clearance angle must be modified, and an example will illustrate this point.

Suppose that the cutter in the previous example is to have the same clearance angle, i.e. a normal clearance of 8°, and that the teeth have a helix angle of 35°, what is the value of the axial clearance angle?

Using the result found above, we have:

$$\begin{aligned} \tan \theta_a &= \tan \theta_n \cos a \\ &= \tan 8° \times \cos 35° \\ &= 0{\cdot}1405 \times 0{\cdot}8192 \\ \tan \theta_a &= 0{\cdot}1150 \end{aligned}$$

Hence, $\theta_a = \tan^{-1} 0{\cdot}115$

$$\theta_a = 6° \, 34'$$

This is the angle which must be used for the setting of the tooth rest to position the cutter teeth for grinding.

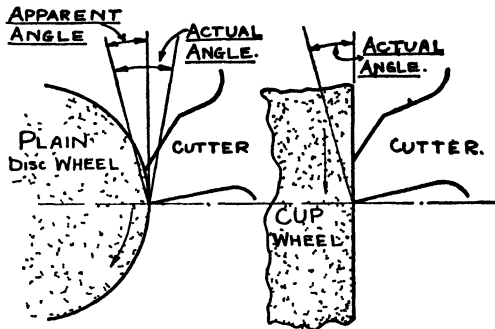
When grinding the tooth of a cutter as in the foregoing examples, the direction of the cut can be from the back to the front of the tooth or from the front of the tooth to the back. In the first of these methods, the wheel presses the face of the tooth on to the tooth rest but the wheel raises a burr on the cutting edge. The burr must be removed by stoning, and there is a tendency to draw the temper of the steel. The other method rotates the wheel from the cutting edge towards the body of the tooth, and it results in less danger of burning the tooth, but great care must be used to hold the cutter against the tooth rest.

This applies to both methods of grinding, i.e. to grinding with a disc wheel and grinding with a cup wheel.

FIG 131

There is another point to be observed in connection with tooth grinding, and this concerns the question of the use of the wheel, whether cup or disc wheel. In general, the plain or disc wheel may be used for narrow lands, but the cup wheel should be employed for wide lands.

However, the plain wheel may be tilted in such a way that the cut will approach a straight line. Plain wheels are used on cutters up to 4 in. in diameter and cup wheels for cutters larger than 4 in. diameter. The putting of clearance in cutter teeth by the two methods just described is further illustrated in Fig. 131, in which the conditions producing clearance by both cup and disc wheels is shown in an exaggerated manner.

From the sketch it will be seen that in using a disc wheel the actual angle at the cutting edge is much greater than the apparent angle. The apparent angle must be large enough to ensure that the heel of the tooth will not drag on the work when the cutter is in use.

Clearance

Correct clearance at the back of the cutting edge is, of course, essential. If it is insufficient, it will cause the teeth to drag over the work, resulting in increased friction and slow cutting, whilst, on the other hand, too much clearance will cause the teeth to wear rapidly and produce chatter. However, of the two too much clearance is preferable to too little. The tooth edge must be sharp and the clearance angle correct. A secondary clearance angle of 9–30°, depending on the design and type of cutter, pro-

duces a stronger tooth and gives a means of controlling the width of the land, which should be about $\frac{1}{32}$–$\frac{3}{64}$ in.

The land and secondary clearance are shown in Fig. 132.

RELIEVED CORNER OF FACE MILL TOOTH.

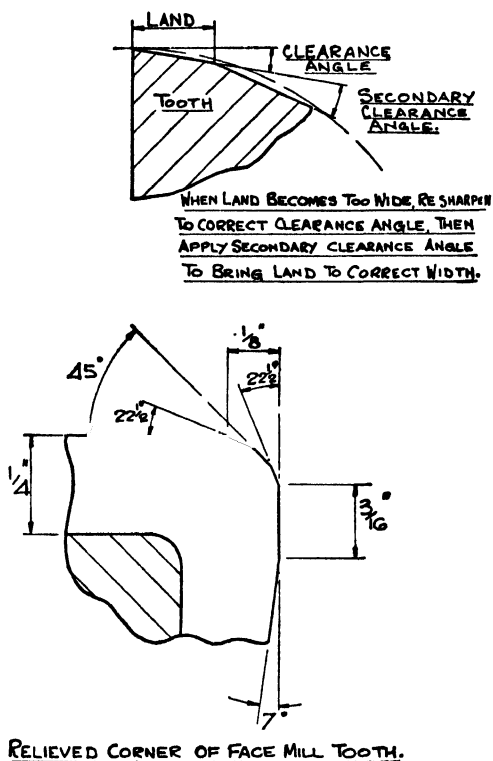



FIG. 132

Below is a table which gives average values for clearance angles for average cutters. The values may be slightly less for large cutters and slightly increased for small cutters.

TABLE 11

Material	*Clearance °*
Low/Medium carbon steel	0–7
Hard steel	2½–6
Steel castings	6–7
Cast iron	3–7
Bronze (Cast)	10–15
Copper	12–15
Aluminium	10–12

The clearance angle is produced by properly locating the wheel, cutter and tooth rest, as has already been seen. In setting the cutter the amount h (see Fig. 128) can be obtained by multiplying the clearance angle in degrees by wheel diameter in inches by 0·0088. The product of these three items will give the distance in thousandths of an inch through which the cutter and tooth rest must be raised or lowered in order to obtain the correct clearance angle. This method is for a plain or disc wheel setting.

$$h = \theta^\circ \times D_w \times 0{\cdot}0088$$

For a cup wheel the setting is obtained by multiplying the clearance angle in degrees by the *cutter* diameter in inches by the constant 0·0088:

$$h = \theta^\circ \times D_c \times 0{\cdot}0088$$
$$\therefore h = 0{\cdot}0088\ \theta D_c$$

Example.—To find the setting for grinding 5° clearance angle on a 2-in. diameter cutter using a cup wheel:

$$h = 0{\cdot}0088 \times 5 \times 2 = 10 \times 0{\cdot}0088$$
$$\therefore h = \mathbf{0{\cdot}088\ in.}$$

For a plain wheel the cutter diameter does not matter. It is the grinding-wheel diameter which must be taken into account.

Example.—Find the setting for grinding 5° clearance on 2-in. cutter using 4-in. diameter disc wheel:

$$h = 0{\cdot}0088 \times 4 \times 5 = 20 \times 0{\cdot}0088$$
$$h = \mathbf{0{\cdot}176\ in.}$$

Typical uses of the tool and cutter grinder are shown in Figs. 133 and 134, in which the setting for grinding the dies for Herbert "Coventry" Dieheads using plain wheels on the Herbert Tool and Cutter Grinder are illustrated.

Optical Profile Grinder

An interesting development in, and addition to, the field of grinding is found in the Wickman Optical Profile Grinding Machine which is shown in Fig. 135.

This machine will finish grind any desired regular or irregular shape within its capacity and range. It will grind flat or circular form tools, punches and die segments, profile gauges, special shapes, such as profile cams, templates, and any other special shape or profile, including tungsten-carbide material. It will produce these articles to a high degree of accuracy.

The operation of the machine in producing the parts mentioned includes a pantograph mechanism for obtaining the profile desired by transferring the contours on the drawing or workpiece to the work through a lever system. The machine employs a layout drawn to 50 times full size, i.e. 50 times the size of the profile to be ground, and a microscope is carried on the short arm of the 50 : 1 pantograph.

The long arm of the pantograph carries a pointer which is moved by the operator from point to point along the line of the lay-out. The work

FIG 133—GRINDING DIES ON TOOL AND CUTTER GRINDER

Courtesy Alfred Herbert Ltd.

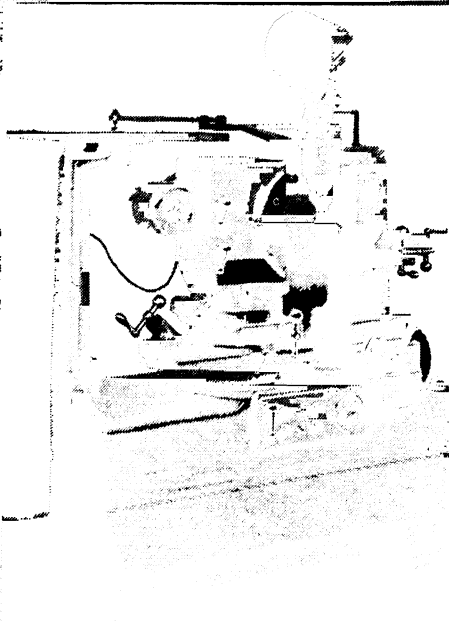
FIG. 134—TOOL AND CUTTER GRINDER HEAD-GRINDING DIES

Courtesy A C Wickman Ltd

FIG. 135—OPTICAL PROFILE GRINDER

is focused in the microscope, in which is seen a graticule carrying cross-hair lines. The intersecting point of the graticule lines corresponds to the position of the pointer on the 50 : 1 lay-out.

The grinding wheel is manually fed to the intersection of the cross-hair lines after each movement of the pantograph arm and its exact position is observed through the microscope.

Because of the fact that the wheel is always fed up to a predetermined point, accuracy is not affected by wheel wear. An accuracy of dimension to within 0·0005 in. may be obtained, and with reasonable care on the part of the operator closer limits are possible.

FIG. 136—ARRANGEMENT OF WORK AND PROFILE ON WICKMAN PROFILE GRINDER

Actually, the optical profile grinder is a combination of a universal grinding machine and a microscopic inspection device. The grinding head, consisting of slides and circular guides with vernier graduated scales, carries a grinding wheel reciprocating in a vertical or oblique direction. The slides can be set at any desired angle to each other and to the work. This permits the grinding wheel to move in any required direction and to grind surfaces of any angular position. Moreover, the work is viewed in the operating plane, even when a clearance angle is being ground, but compensations must be made in the lay-out when top rake angles are being ground.

The wheel has a stroke of 2 in., and this permits a number of thin pieces to be ganged together, a feature particularly valuable when making small quantities of precision parts which must be identical. The capacity of the machine is such that it will grind a form $5\frac{7}{8}$ in. long, $2\frac{1}{2}$ in. wide and 2 in. deep, i.e. it will grind a form in a form tool $5\frac{7}{8}$ in. long and $2\frac{1}{2}$ in. in depth in material 2 in. thick. The tool or work can, however, be of unlimited length and up to $6\frac{3}{4}$ in. wide.

However, it should be noted that profiles with an area greater than 0·4 sq. in. must be dealt with in sections.

From the views shown in Figs. 135 and 136, the general points of the machine and its design can be followed. The board on which the lay-out is placed, the pantograph tracing point, the optical system and the various guides for obtaining the required motions and positions can be clearly seen.

A line diagram showing the relationship between the lay-out profile and the work is given in Fig. 136.

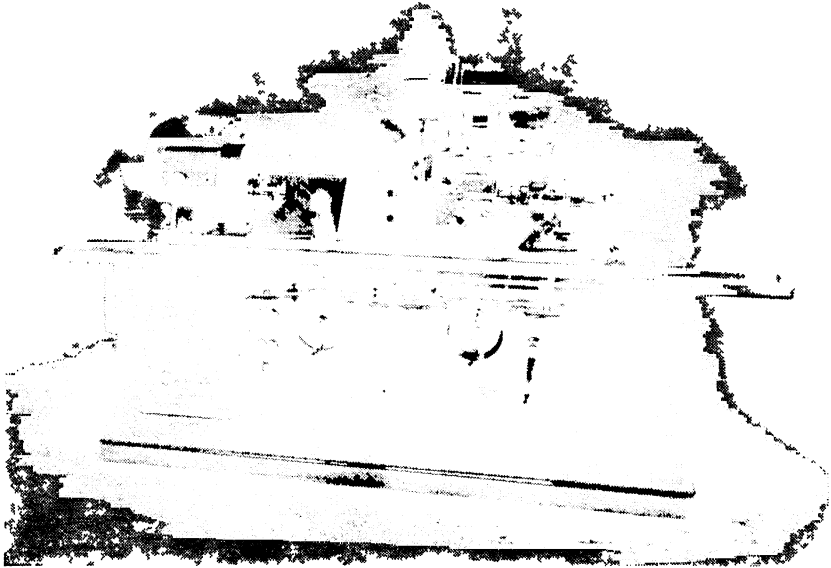
This indicates the pantograph mechanism, the layout and the work, and the view seen through the microscope. A point P on the work, corresponding to a point P_1 on the enlarged layout profile, would be viewed in the microscope directly above the work. The view of the cross-

Courtesy Churchill Machine Tool Co Ltd

FIG. 137—CHURCHILL PBW 12 IN. × 36 IN. UNIVERSAL GRINDING MACHINE

hairs of the instrument and profile of the part under inspection is shown in the circle. By using this method no further inspection of the work is necessary, and by reversing the process and placing a workpiece or part in the machine, a magnified contour of the part can be traced 50 times the work size. This can be used to obtain a 50 : 1 drawing of any previously unknown or unrecorded profile or form.

Universal Grinders

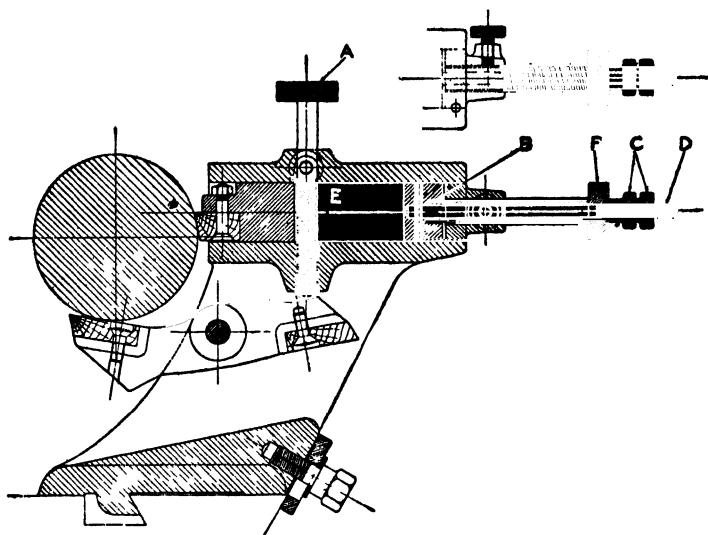
The most useful and versatile machine is the universal grinder, a view of which is shown in Fig. 137, and it will be noted that the machine is fitted with work steadies, three being shown in position on the table. On all cylindrical work steadies should be used in order that the work may be ground truly cylindrical. The design of a steady for use with the Universal Grinding Machine is shown in Fig. 138, from which it will be seen that the block holder E is fed by screw F to the desired position,

Courtesy Churchill Machine Tool Co. Ltd.

FIG. 138—WORK STEADIES

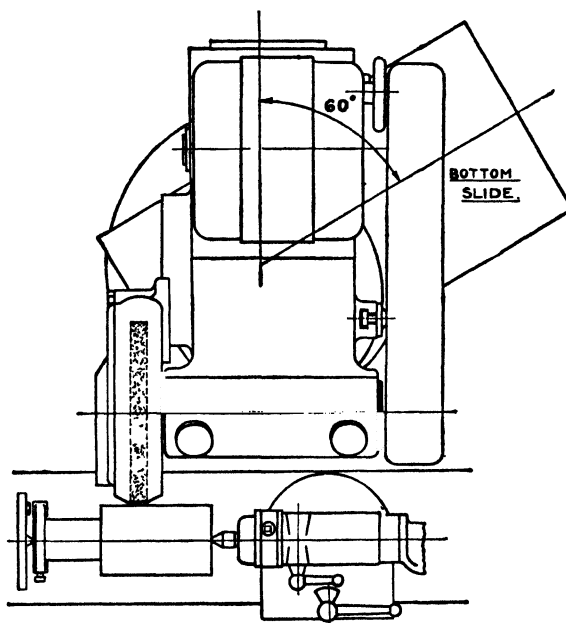



FIG. 139—METHOD OF OBTAINING EXTRA FINE FEED ON UNIVERSAL GRINDING MACHINE

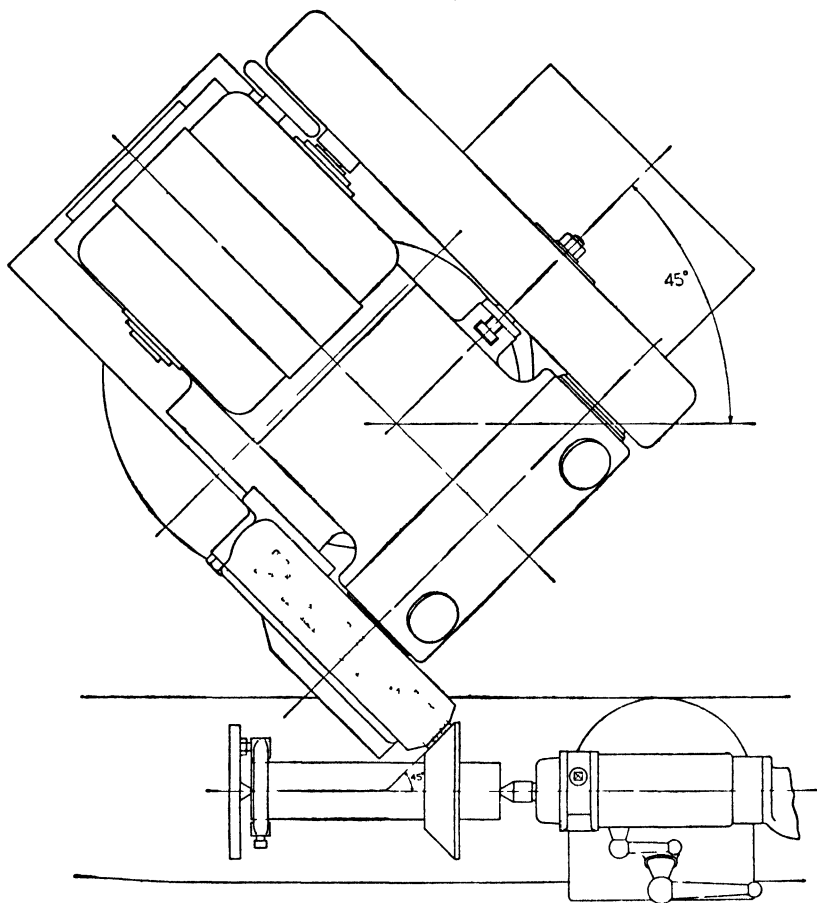
and the required pressure on the work is controlled by spring *B*, adjusted by screw *D* and nuts *C*. The work is put in a state of tension by screw *A*, which, when the required tension has been obtained, is locked in position, and the necessary tension in the work is automatically retained by reason of the work trying to regain its normal position. The universal machine

Courtesy Churchill Machine Tool Co. Ltd

FIG 139A—GRINDING TAPER ON UNIVERSAL MACHINE

can grind work either between centres—as in ordinary cylindrical grinding—grinding tapers and conical tapers (see Figs. 139 and 139A) and also can produce flat surfaces Certain types of work cannot be accommodated in centres, and for these cases various attachments are available, chiefly a four-jaw independent chuck, large faceplate and faceplate chuck with expanding collet.

In Figs. 139 and 139A conical and cylindrical surfaces are generated, and

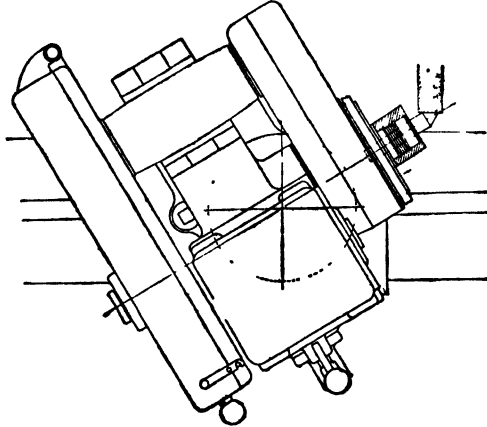
in both cases the wheelhead has been swivelled round, in Fig. 139A through 45° to obtain the desired taper, and in Fig. 139 through 60° in order to obtain a finer feed than that directly obtainable by normal cross feed. The full feed acting along the slide at 60° is reduced when applied to

Courtesy Churchill Machine Tool Co. Ltd.

FIG 140—TRUING WORK CENTRES ON UNIVERSAL GRINDING MACHINE

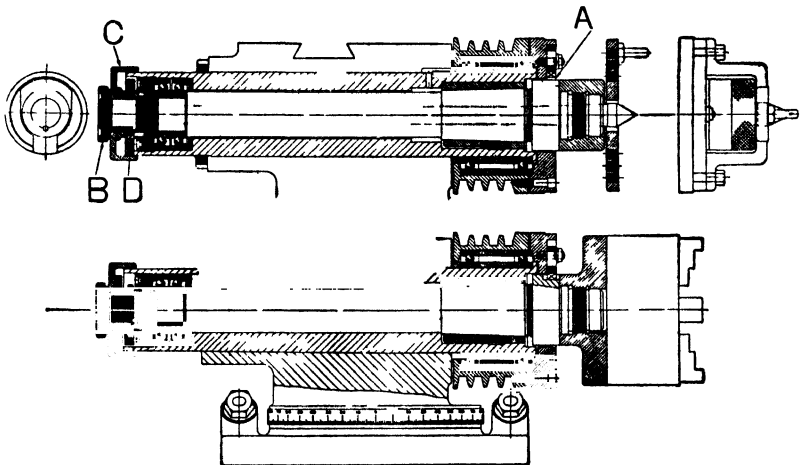
the work by the wheel moving in towards it in the manner shown. The setting shown in Fig. 139 reduces the normal feed by one-half, and results in an extra fine feed. This fine feed is useful for work such as gauges. The 60° set over results in the feed being applied at 30° and giving a feed of $\frac{1}{16000}$ in. (0·0000625 in.).

Courtesy Churchill Machine Tool Co. Ltd.

FIG. 141—UNIVERSAL WORKHEAD

The Universal Workhead

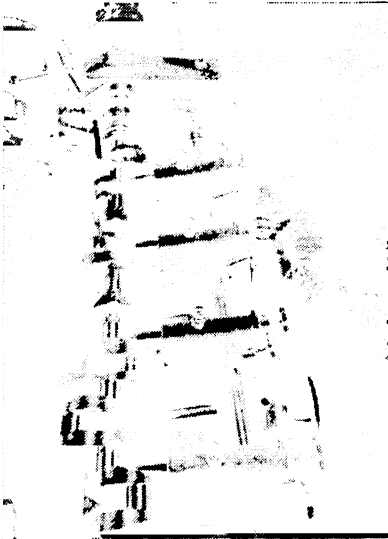
This unit is shown in Fig. 141, which illustrates a Churchill Universal Grinder Workhead in part section. The drive is from a motor (constant speed) mounted on an adjustable base just above the work spindle, via

Courtesy Churchill Machine Tool Co Ltd

FIG. 142—SHOWING STEADIES IN POSITION FOR GRINDING JOURNALS OF HEAVY CRANKSHAFT

FIG. 143—METHOD OF BALANCING A GRINDING WHEEL

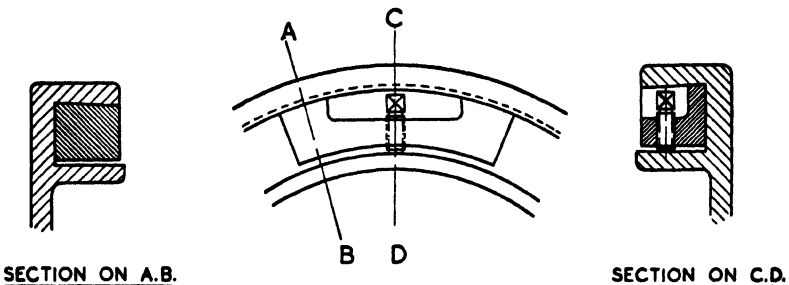
vee belts to a countershaft secured at the rear of the workhead. As will be seen on reference to Fig. 141, the vee pulleys have four grooves, and the faceplate is bolted to the vee-belt pulley, which takes the secondary drive from the countershaft. The pulley runs on ball journal bearings and is free to rotate about the spindle housing, which is integral with the main workhead casting. In this form it is a dead-centre drive, and can

Courtesy Churchill Machine Tool Co. Ltd.

FIG. 144—BALANCE WEIGHT USED IN SPECIAL BALANCED COLLET

be converted to a live spindle drive by engaging finger A recessed in the faceplate with a corresponding slot in the work spindle flange and locking it in position. The knurled nut *B* at the end of the spindle is then removed, allowing removal of cover *C*, which exposes a small disc *D* keyed to end of work spindle. This disc must be reversed on the spindle to disengage the lug from the slot on the spindle, and thus allow the spindle to rotate freely. The cover and nut should be replaced.

Most of the points just dealt with can be seen in Fig. 142, which shows a heavy crankshaft with four steadies in position for the operation of grinding the journals. On the left the grinding wheel can be seen, and in connection with grinding wheels it should be remembered that perfect balance should be obtained. The method of balancing is shown in Figs. 143 and 144.

For all except small wheels, a special balance collet is used, embodying a dovetail groove in which a movable weight can be easily fitted and adjusted (see Fig. 144), whilst the wheel and the collet is mounted on the balancing ways shown in Fig. 143. The method employed to balance a wheel is as follows: first remove balance weights from collet, mount the grinding wheel and place collet on the machine spindle. True up the wheel with a diamond, remove wheel and collet, and mount them on an arbor as shown in Fig. 143, and test for balance on the balancing ways. If the wheel is not in balance, it will revolve when the heavier part is above the centre of the wheel. To obtain balance, the four weights are inserted and then adjusted until the wheel is correctly balanced. The ways used for balancing the wheel should be parallel to each other and strictly horizontal.

Exercises on Chapter V

1. Describe the theory of grinding, and show by sketches the relative velocities of work and wheel.

2. What do you understand by cylindrical grinding ? Sketch the wheel, work and important parts in a plain cylindrical grinding operation.

3. How many types of surface grinding machines are there ? Sketch, in a line diagram, the essential difference between the types you have mentioned.

4. How does centreless grinding differ from other types of grinding ?

5. (*a*) How is the feed arranged for in a centreless grinder ? (*b*) Give an expression for finding the feed.

6. Using the formula called for in Question 5, calculate the feed in inches per minute for the following:
(*a*) Control wheel 10 in. diameter, making 52 r.p.m., set over 5°.
(*b*) Control wheel 12 in. diameter, making 70 r.p.m., set over 6°.
(*c*) Control wheel 8 in. diameter, making 30 r.p.m., set over 3°.

7. Describe the methods generally used for tool and cutter grinding and show by sketches the conditions for this operation:
(*a*) Using plain or disc wheel.
(*b*) Using cup wheel.

8. (*a*) Calculate the setting for grinding a cutter 2½ in. diameter to have 5° clearance for both disc wheel and cup wheel. (*b*) How would this be affected if the clearance angle were to be increased to 7° ?

CHAPTER VI

LATHES

LATHES generally can be classified into four main groups:

(a) The centre lathe.
(b) The capstan lathe.
(c) The turret lathe.
(d) The automatic lathe.

The capstan and turret lathes have already been dealt with in Chapter III, and no further detail is needed here; therefore only the centre lathe and the automatic lathe, or auto as it is termed, will be considered in this chapter.

The types of lathe in group (a) are numerous, far too numerous to be dealt with in a single chapter of this nature, and only the principles underlying their operation and usefulness can be considered. Centre lathes vary in size, from the small watch- and clock-maker's lathe to the huge tube-boring lathes so large that anti-friction bearings for spindle are of a size 86 in. diameter outside, and so long that a special carriage is attached to the saddle, on which the operator stands and is carried along with it. In between these extremes is a multitude of sizes, models, types, etc., including those with double beds carrying two saddles, and it must of necessity be left to the student's own initiative to investigate these varying types and supplement the information contained in this book by reference to handbooks or specialist publications.

Generally, in the normal centre lathe there is only one cross-slide tool and one axial tool, although the square tool post and the various patent small tools now available increase the range of operations. There are still a number of back-geared lathes in use, and this type is still made for small bench lathes, the chief use of a back gear being to reduce speed, mainly by increasing the number of speeds, and thus obtain extra power for dealing with excessive or heavy cuts.

Some points referring to lathes have been dealt with in previous chapters, and it now only remains to consider the main details of its construction.

Headstock

The modern lathe has an all-geared unit drive and is independent of any countershaft, the electric motor drive to the geared headstock being

self-contained, allowing the lathe to be located in any suitable position. The actual gears themselves are arranged on the Geometric Progression speed ratio (see Chapter II), and by this means the spindle can be driven at speeds suitable for the work in hand. The spindle, when driving the work, either by means of a chuck or carrier and faceplate, in conjunction with the cutting tool, generates a cylinder when it moves along with the carriage. When the tool is fed across the work (cross traverse), it generates a flat face on the end of the work, and at other positions it would produce grooves or formed portions if such tools were used in the cross slide.

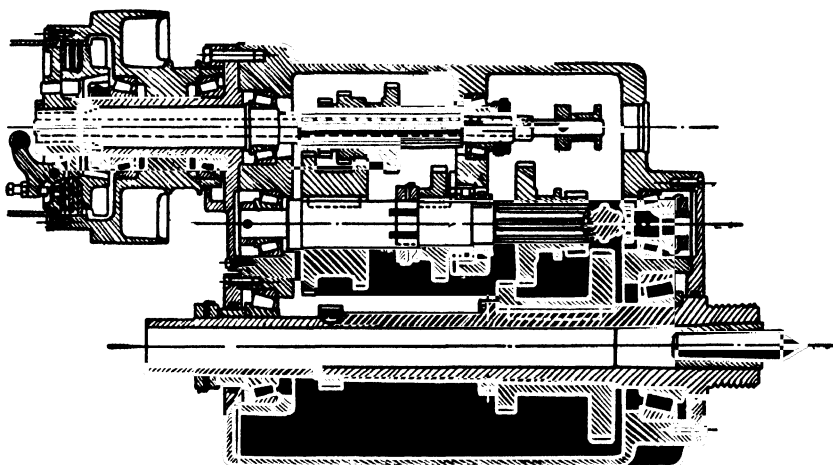
In addition to these operations, the lathe is often used for thread cutting, which is performed by arranging the work rotation in correct

Courtesy British Timken Ltd.

FIG. 145—ALL-GEARED LATHE HEADSTOCK

relationship with the travel of the cutting tool to produce a thread of the desired lead. The work dealt with in this book is mainly for students in the fourth and fifth years of the Production Engineering Courses for Higher National Certificates in Production Engineering, and they will therefore have dealt with some of this work in their third year in Workshop Technology classes. This being so, it is not proposed to duplicate this work to any great extent. Other operations of the lathe are the turning of tapers and spherical portions, either by using radius tools or special attachments.

Returning to the headstock, a typical design for an all-geared lathe headstock, the spindles and clutch of which are mounted on Timken Taper Roller Bearings, is shown in Fig. 145.

There are many designs of headstock, and some of these are shown in the accompanying illustrations, and in Chapter III, Figs. 38–43.

Perhaps the most noteworthy of the headstock designs is the Herbert Preoptive Head. This design of headstock enables preselected speeds to be obtained whilst the spindle is running and whilst the tool is cutting, and the Preoptive Head is fitted to the Herbert Capstan and Turret Lathes. In this Herbert Preoptive Headstock any one of the eight speeds, from 42 to 1,000 r.p.m., can be preselected by merely rotating the dial on the front of the headstock. When the speed is required, finger pressure on the button in the centre of the dial effects the change instantaneously. This instantaneous change of speed under cut is made possible by the elimination of sliding gears, the actual change being made by the power operation of highly efficient multi-disc friction clutches.

The above points are illustrated in Figs. 146 and 147. The method of operation of the headstock is as follows:

Pre-selection of Speeds

Referring to Fig. 146, the rotation of the pilot wheel *A* on the change-speed dial rotates through gearing the shaft *B*, on which are mounted two selector discs *C* and *D*, which slide axially on the shaft.

The radial position of the selector discs for the eight speeds marked on the dial are located by a star cam on shaft *B*. Mounted above the selector discs are three rods which slide in holes in the headstock casting. Each rod carries a glut, which operates the slider of one of the three double multi-disc clutches which can be seen in Fig. 146. On the lower end of each glut is a lug which engages with the projections on the selector discs.

The effect of rotating the selector discs by pilot wheel *A* is to bring into the top position the required combination of projections on the discs to move each of the sliders on the three clutches either right or left according to the speed indicated on the dial.

Changing Speeds

A $\frac{1}{8}$-h.p. motor-stator unit *E* (Fig. 147), controlled by a push-button below the feed-box, is continuously running during a machining operation which involves speed changes. The motor drives the wormwheel *F* which is mounted on the same shaft as the barrel cam *G* and radial cam *H*.

The cam *G* is spring loaded towards the wormwheel, engagement between the two being effected by a dog clutch. The cam is withheld from engagement by lever *J*, one arm of which engages with the cam groove.

When the knob of the pilot wheel is depressed, the arm on the opposite end of the lever is moved, thus withdrawing the arm from the cam groove.

The cam moves to the left to engage the dog clutch, thus rotating the radial cam *H* which operates a spring-loaded plunger, and hence the bellcrank levers *K*.

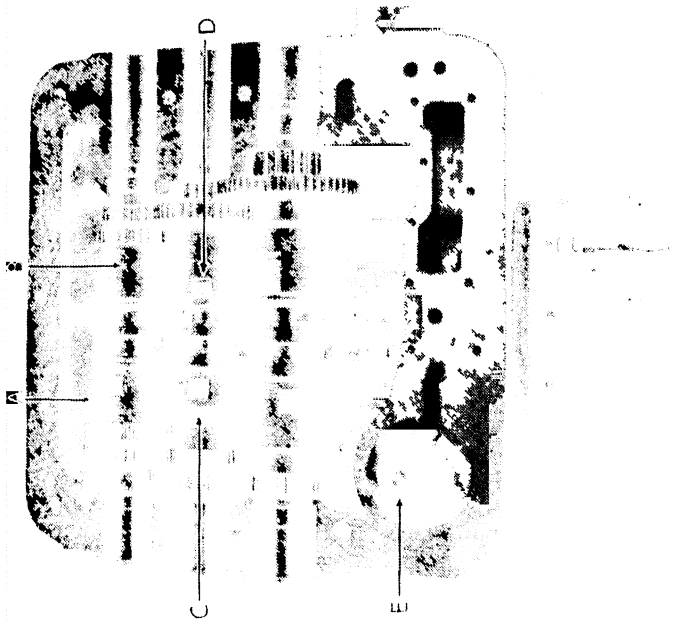
These levers engage with the selector discs, which are moved inwards to actuate the gluts operating the clutches.

Courtesy Alfred Herbert Ltd

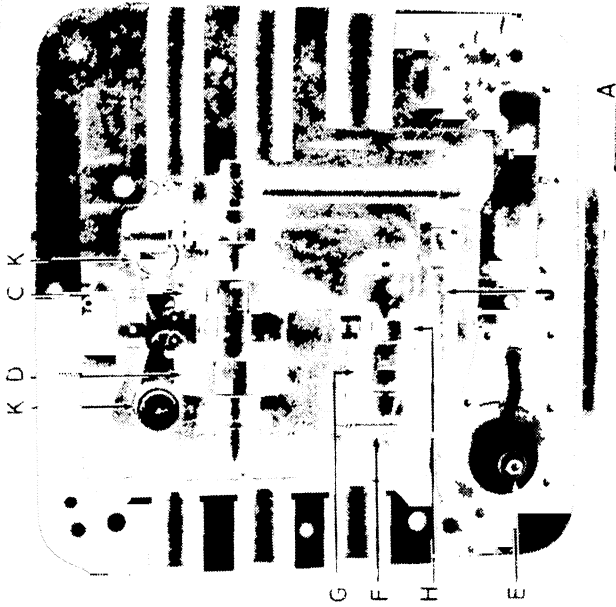
FIG 146—CLUTCHES AND GEARS OF PREOPTIVE HEADSTOCK

Courtesy Alfred Herbert Ltd

FIG 147—CAMS, LEVERS AND SELECTORS, PREOPTIVE HEADSTOCK

Before the cam G has made a complete revolution, the lever drops into the groove, which is in the form of a dog's leg, and the cam is withdrawn from engagement with the wormwheel.

An interlock prevents the speed engaging knob being operated if the speed dial is not in the correct position to locate the selector discs in any of the positions corresponding to the eight speeds.

The clutches are shown in Figs. 146 and 147, four of these clutches, A, B, C and D, are adjustable, but the two larger clutches at the front of the headstock are spring loaded and do not require adjustment.

Each clutch must be adjusted with the speed dial set to give the speed which will disengage the clutch. For the adjustment of clutch A, for example, the dial is set to 177 r.p.m. and the change-speed knob pressed. When the power has been cut off from the machine by the isolating switch, special keys and spanners supplied with the machine are used, and in this case the special clutch adjusting key with end marked A is inserted in the hole above the clutch, so that the end of the key engages with a slot in the clutch cam plate. The keys are spring loaded so that they are self-releasing.

A $\frac{7}{16}$-in. Whitworth box spanner is then engaged with the hexagon head of the pulley shaft, which is turned by this means in an anti-clockwise direction to move the pressure plate one or two notches.

The ease of operation of this headstock is dealt with in Chapter III in the section dealing with Capstan Lathes.

Leadscrew and Feedshaft

The leadscrew and feedshaft of the lathe are driven from the spindle by means of gearing, a tumbler gear being used for reversing the direction of rotation. This gearing is variable by means of change wheels to give different threads per inch or rates of feed.

For screw cutting in the lathe we have the following. The thread on the leadscrew is common for all threads cut on a given machine, and since it receives its rotation directly from the lathe spindle via the gears and clasp nut (nut box or half nuts), it is a comparatively simple matter to rotate the leadscrew in any given relationship to the spindle and the work it carries. Thus, if a leadscrew has 4 threads per inch, i.e. $\frac{1}{4}$-in. pitch thread, and a screw having 8 threads per inch is to be cut, then the leadscrew will have to be geared down in the ratio of $\frac{8}{4} = 2:1$, or, in other words, the threads cut per inch in work are twice those on the leadscrew, which is the required condition.

The gear ratio then is $\dfrac{\text{Number of teeth in driver}}{\text{Number of teeth in follower}} = \dfrac{\text{Pitch to be cut}}{\text{Pitch of leadscrew}}$

i.e. $$\frac{\text{Spindle gear}}{\text{Leadscrew gear}} = \frac{T_D}{T_F} = \frac{8}{4} = \frac{8}{4} \times \frac{5}{5} = \frac{40}{20} \text{ or } \frac{80}{40}$$

Therefore, a 40-tooth wheel on the spindle will drive an 80-tooth wheel on the leadscrew.

The ratio $\frac{\text{Spindle gear}}{\text{Leadscrew gear}} = \frac{T_D}{T_F}$ is for a simple train.

Not all cases, however, can be solved by the use of a simple train of gears, and a compound gear train must be used in which the relationship is:

$$\frac{\text{Pitch to be cut}}{\text{Pitch of leadscrew}} = \frac{\text{Number of teeth 1st driver}}{\text{Number of teeth 1st follower}} \times \frac{\text{Number of teeth 2nd driver}}{\text{Number of teeth 2nd follower}}$$

$$= \frac{T_{D1}}{T_{F1}} \times \frac{T_{D2}}{T_{F2}}$$

Example.—Find the wheels necessary to cut a thread 11 threads per inch on a lathe whose leadscrew is $\frac{1}{4}$-in. pitch:

$$\text{Gear ratio} = \tfrac{4}{11} = \frac{\text{Drivers}}{\text{Driven}} = \frac{\text{Driver}}{\text{Follower}} = \frac{T_{D1}}{T_{F1}} \times \frac{T_{D2}}{T_{F2}}$$

$$\tfrac{4}{11} = \tfrac{1}{2\cdot 2} \times \tfrac{4}{5}$$

$$= \left(\tfrac{1}{2\cdot 2} \times \tfrac{30}{30}\right) \times \left(\tfrac{4}{5} \times \tfrac{10}{10}\right)$$

$$= \tfrac{30}{66} \times \tfrac{40}{50}$$

That is, a 30-tooth wheel drives a 66-tooth wheel and on the same shaft a 40-tooth wheel drives a 50-tooth wheel on the leadscrew of the lathe, which in turn gives the required motion to the cutting tool.

When calculating compound trains of gears, the gear ratio is divided up so that the factors found give the original ratio when multiplied together.

From the foregoing it will be clear that the lead to be cut on any desired thread will be given by:

$$\frac{\text{Product of drivers}}{\text{Product of driven}} \times \text{leadscrew lead} = \text{lead cut}$$

When single threads are being cut the lead is the same as the pitch.

Multi-start Threads

In cutting a multi-start thread it is necessary to find the lead of a single thread before calculating the gear train required. This can readily be done by dividing the number of thread starts by the threads per inch,

e.g. the lead of a multi-start screw thread of 20 threads per inch having 4 starts, i.e. a quadruple thread, is

$$\text{Lead} = \frac{\text{Number of starts}}{\text{Threads per inch}} = \tfrac{4}{20} = \tfrac{1}{5} = \textbf{0·2-in. lead.}$$

The gear train must be arranged therefore to cut a thread of 0·2-in. lead, i.e. a 5 threads per inch screw.

The gears can then be found as for previous examples. If, however, the pitch of the thread and number of starts is given, the problem is resolved thus:

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{\text{Pitch} \times \text{Number of starts}}{\text{Pitch leadscrew}}$$

Example.—Find the gears required to cut a triple thread 0·4 in. pitch on a lathe with a leadscrew of 4 threads per in. Thread to be cut is a 3-start thread:

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{0{\cdot}4 \times 3}{\frac{1}{4}} = \frac{1{\cdot}2}{0{\cdot}25} = \frac{4{\cdot}8}{1}$$

$$= \tfrac{48}{10} = \tfrac{240}{50}$$

$$= \tfrac{240}{50} \times \tfrac{10}{10} = \tfrac{120}{50} \times \tfrac{10}{5} = \tfrac{60}{25} \times \tfrac{100}{50}$$

$$\text{i.e. gears} = \tfrac{60}{25} \times \tfrac{100}{50}$$

Metric Pitches

To cut metric pitches on a leadscrew with a thread in inches or vice versa requires a modification in the nature of the relationship between the two units of measurement. The method will be clear from a consideration of the following example:

Find the gears required to cut a 6-millimetre pitch thread on a lathe with a leadscrew having 4 threads per inch.

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{\text{Lead to be cut}}{\text{Lead of leadscrew}} \times \frac{1}{25{\cdot}4}, \text{ since 1 in.} = 25{\cdot}4 \text{ mm.}$$

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{6}{\frac{1}{4}} \times \frac{1}{25{\cdot}4} = \frac{6 \times 4}{1} \times \frac{1}{25{\cdot}4}$$

$$= \frac{24}{1} \times \frac{10}{254} = \frac{6 \times 4}{1} \times \frac{5}{127}$$

$$= \tfrac{12}{1} \times \tfrac{10}{127} = \tfrac{120}{127}$$

Because of the fact that in 1 in. there are 25·4 millimetres, a wheel having 127 teeth must be used when cutting metric threads on a leadscrew with English dimensions and when cutting a thread in inches on a metric leadscrew.

Square Threads

When cutting square threads the question of gearing is exactly the same as all the foregoing examples. The depth of the thread and the

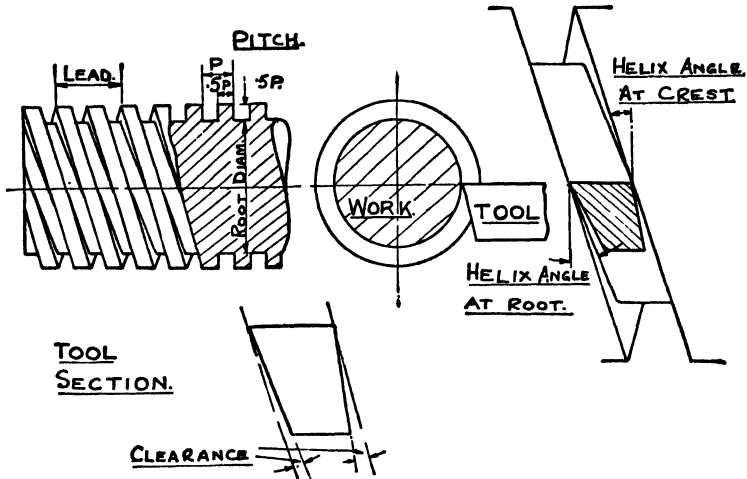



Fig. 148

pitch (or rather lead) of the thread has to be considered when grinding the tool for cutting the thread. In Fig. 148 the conditions obtaining are shown, and an example should indicate the method.

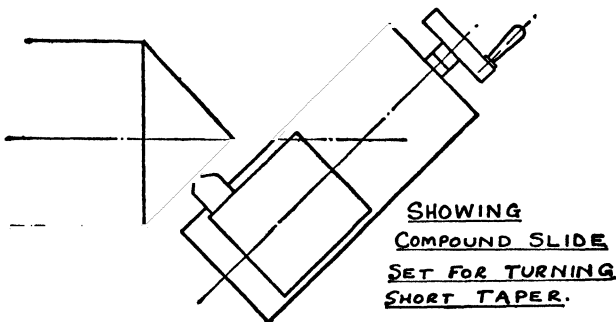



Fig. 149

Find the angles and tool width required to cut a 2-start square thread, 1 in. lead on a 3-in. diameter shaft. Allow 3° clearance on both sides of the tool, the top edge of which is to be parallel to the axis of the screw thread.

Since the thread is double, i.e. a 2 start thread, the pitch = half lead = $\frac{1}{2}$ in. From the proportions of a square thread, the width of thread form is

$$\frac{\text{Pitch}}{2} = \frac{\frac{1}{2}}{2} = \frac{1}{4} \text{ in.}$$

$\therefore$ Tool width = $\frac{1}{4}$ in. = **0·25 in.**

Now the effective diameter of the thread = 3 − $\frac{1}{4}$ in. = **$2\frac{3}{4}$ in.**

$$\text{Tan of helix angle} = \frac{\text{Lead}}{\pi d_{\text{mean}}} = \frac{1}{\pi \times 2\frac{3}{4}} = \frac{4}{\pi \times 11}$$

$\therefore$ Helix angle = **6° 36′.**

Taking the root diameter of thread: Root diameter = $2\frac{1}{2}$ in.

$$\tan \alpha_{\text{root}} = \frac{1}{2{\cdot}5\pi} = \mathbf{7° \ 16'.}$$

Leading angle = 90 − 7° 16′ − 3° = **79° 44′.**

Taking the crest diameter, $\tan \alpha_{\text{crest}} = \frac{1}{3\pi} =$ **6° 3′.**

Following or trailing angle = 90 + 6° 3′ − 3°
= **93° 3′.**

If the mean diameter had been used, the angles would have been:

Leading angle = 90° − 6° 36′ − 3° = **80° 24′**
Trailing angle = 90° + 6° 36′ − 3° = **93° 36′**

For fine pitches the mean or effective diameter of the thread is used. For the coarser pitches the root and crest diameters are taken in order to find the helix angle α at the top and bottom of the thread.

Fine pitch:

$$\tan \alpha = \frac{\text{Lead}}{\pi d_{\text{mean}}} = \frac{\text{Lead}}{\pi d_m}$$

For coarser pitch:

$$\text{Leading edge, } \tan \alpha = \frac{\text{Lead}}{\pi d_{\text{root}}}$$

$$\text{Trailing edge, } \tan \alpha = \frac{\text{Lead}}{\pi d_{\text{crest}}}$$

From the sketch showing the conditions, it will be clear that the root and crest diameters must be used in order to find the angles required for cutting a given square thread.

Taper Turning

The turning of tapers or production of conical surfaces on the lathe is another important operation. There are three methods used:

1. Setting over the tailstock.
2. Setting the compound slide and formed tool.
3. Taper turning attachment.

Fig. 150 shows the first two methods which are more or less self-explanatory. The formed tool and use of the compound slide is only suitable for short tapers, whereas the setting over of the tailstock is only

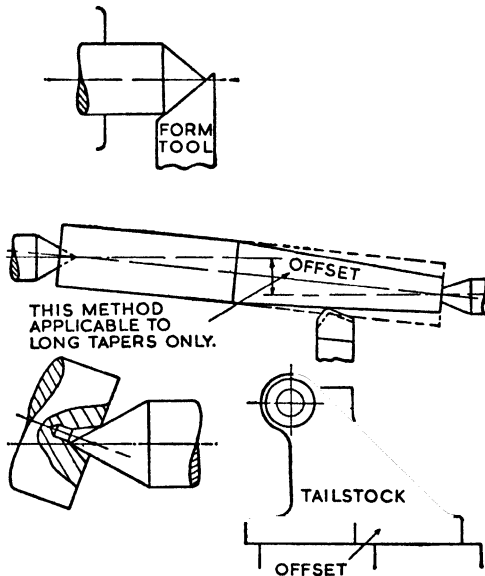



FIG. 150—METHODS OF TAPER TURNING

suitable for long tapers due to the conditions imposed by the centres. The production of taper surfaces by grinding is shown in Figs. 139A and 140.

The Taper-turning Attachment

The principle of the taper-turning attachment is simple, and most attachments are of similar design. The principle is illustrated in Fig. 152, in which a taper-turning attachment is shown with a Herbert Combination Turret Lathe. When the lathe is working normally, the slide is set parallel to the lathe bed, and in the case of the Herbert attachment, the binding screw is tightened and the extension rod unclamped.

Referring to Fig. 152, the main parts of the attachment are the bracket *A*, which is bolted to the back of the cross-slide saddle and carries a slide *B*. On this is mounted a pivoted guide plate *C*, which engages with a slide block *D* attached to the cross-slide screw. An extension rod *E* is fixed to slide *B*, and passes through a bracket in which it can be clamped by a lever at the front of the machine.

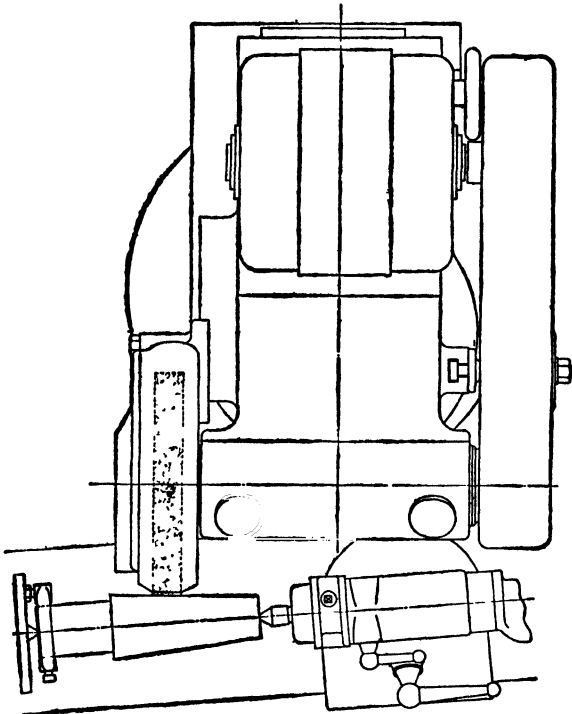
To turn a taper using this attachment, the two square-headed screws *F*

Courtesy Churchill Machine Tool Co. Ltd.

FIG. 151—GRINDING TAPER ON UNIVERSAL MACHINE

in block *C* are first slacked off, and also screw *G*, and the taper guide plate *C* is set to the required taper, using the fine-adjustment screws *H*. Now screw *G* is tightened, the setting checked, and then the screws *F* are tightened up. To obtain a suitable setting for the length of taper to be cut, the extension rod *E* is clamped by means of a lever at the front of the machine, and then the cross slide is moved until the bracket *A* is in a suitable position on the slide *B*. The extension rod is now unclamped, and the taper can be cut.

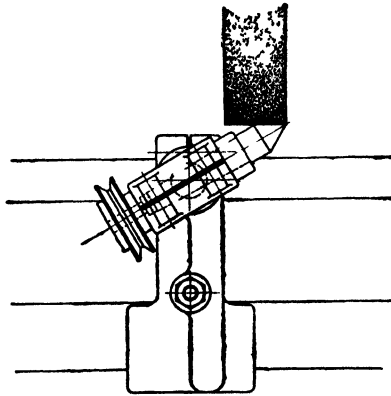
It should be remembered that in cases where there is only one slide on the saddle, the cross-feed screw must be unlocked so that the taper can

Courtesy Churchill Machine Tool Co Ltd

FIG 151A—TRUING WORK CENTRES ON PLAIN GRINDING MACHINE

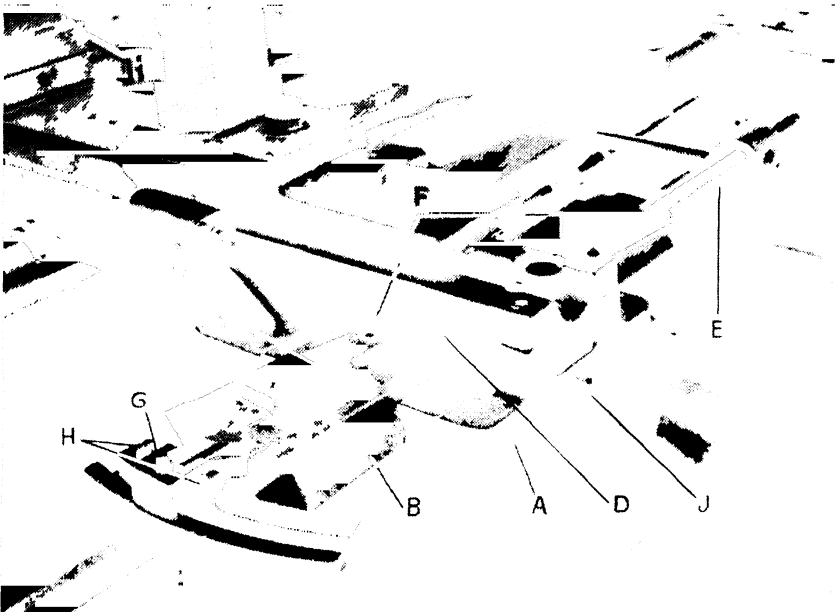
be turned. Where double slides are provided, then the upper slide can be operated by the cross-feed screw in the ordinary way, whilst the lower

Courtesy Alfred Herbert Ltd

FIG 152—TAPER-TURNING ATTACHMENT

slide which carries the whole unit receives the inclined motion from the taper slide. The operation of the taper-turning attachment is illustrated diagrammatically in Fig. 153, in which it will be seen that a slide *A* carries slide block *B* which connects with a cross slide by means of a locking screw *S*. The entire unit is carried on a lower slideway and receives the inclined motion from any set-over of slide *A*, which is set to one-half ($\frac{1}{2}$) the included angle of the taper to be produced. To cut a taper the screw *S* is taken from the normal position *N* and placed in position *T*, where it locks the cross slide to the block *B*.

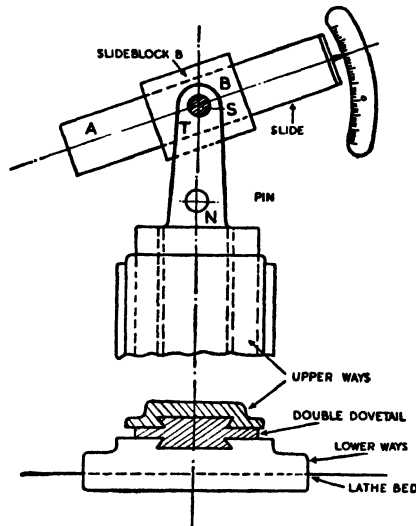



FIG. 153—TAPER-TURNING ATTACHMENT

The conditions obtaining when the tailstock is set over are clearly shown in Fig. 150, and although exaggerated, nevertheless indicate the unsuitability of this method for short tapers or accurate work. The lathe centre at the best of times is a hard-worked unit, subject to high stresses, and these conditions are worsened by the above method.

Example on centre loads to show the operating conditions:

If we consider a centre in either the tailstock or headstock, the area of contact on the work is very small, even when full contact of a centre and work is obtained. The contact area is in the form of a frustum of a cone of 60°. The area is not much more than $\frac{1}{16}$ sq. in.—sometimes less. Taking this figure for purposes of illustration, it will readily be seen that for a tool pressure of only 750 lb. the centre must support 750×16 or 12,000 lb. per square inch. Tungsten carbide tips are of great use in such instances, as are antifriction bearings applied to the centres to facilitate carrying heavy loads.

Lathe Bed

The design of the lathe bed is also important, as this must be rigid and give adequate support to the moving parts. There are many designs, and some of these are indicated in Fig. 154, which show the cross section of a number of typical lathe beds.

Of course, the special lathes, including the capstan, which has a separate slide, and the large turret lathes, sometimes have specially braced structures

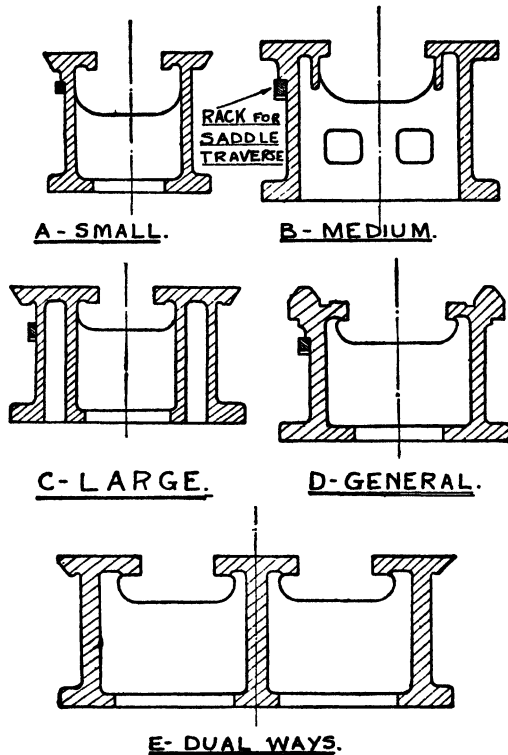



FIG. 154—LATHE BEDS

in order that the bed may be strong in the parts where the greatest stresses are to be encountered.

Referring to Fig. 154(A), the cross section of a small lathe is shown indicating a general type of construction, the ways or shears in this case being flat or rectangular on the surface and insides and vee ways on the two outsides.

Fig. 154(B) shows the cross section of a lathe bed for lathes of medium size. In this instance there is no vee way shown, the ways being rectangular, but modifications of this type are used and vee ways incorporated in some of the designs.

Fig. 154(C) shows a cross section of a large lathe bed, and here again we have the combination of rectangular and vee slideways. In this instance it will be noted that the ways are supported by double pillars forming a box-like construction, and this type is found in the construction of larger sizes of lathes.

Fig. 154(D) shows a type of construction in general use for the smaller and medium-type machines and the vee-type ways are sometimes incorporated in other machines, such as surface grinders and machines of similar nature having a moving table. The combination of the flat and vee ways (or shears as they are sometimes called) provide the support and alignment for the lathe saddle and tailstock (see Fig. 47, Chapter III).

Fig. 154(E) shows a special type of lathe bed for a large lathe designed for large and heavy work. There are dual ways on this bed, and the front and rear ways combine rectangular and vee shears and the centre ways are rectangular only.

Such beds as this can accommodate two saddles as explained elsewhere, and these are sometimes arranged so that one is supported wholly by the front ways and approximately half of the centre ways and the other by the rear ways and half of the centre ways. They can thus be made to operate independently, and thereby extend the use of the machine to which they are fitted.

In all the instances of lathe beds shown it will be noticed that suitable strengthening ribs and built-up construction are employed in order to give the required rigidity and support for the work spindle, etc., when the machine is in operation.

The lathe bed is generally made from a good-quality cast iron, and where possible the stresses within the bed due to the casting and resultant contraction should be minimised by suitable design of the parts and their proportions. After the bed has been cast it should be " aged " or weathered by leaving it in the open to settle down. This is a lengthy process, and where time is an important factor, the same result can be achieved by suitable heat-treatment and stabilising processes, but this involves expensive equipment.

The wearing surfaces can be hardened by chilling or by heat treatment. The ways of the lathes manufactured by Messrs. Alfred Herbert Ltd., Coventry, are flame-hardened, and are shown in Fig. 48, Chapter III, the ways having been hardened to 478/555 Brinell by the " Herbert " " Flamard " process.

Adjusting Strips

Wear on the sliding surfaces is taken up by taper strips or wedges which are placed between the two contact surfaces. The wedges are provided with adjustment, so that when wear takes place it can be compensated for by tightening the wedge and thus maintaining correct sliding fit between the parts concerned.

It is obvious that the nature of flat or sliding bearings is different from a rotary or rolling bearing, and as can easily be seen, the motion of the flat bearing surfaces is reciprocating, the velocity of the contact surfaces is uniform and the pressure between the faces sometimes makes lubrication difficult to maintain. The velocity of rubbing is low when compared with rotary motion, e.g. shaping machine ram compared with lathe spindle, and it is rarely, if ever, above 450 to 500 ft. per minute. On the other hand, the motion of rotary bearings is usually of the order of 2,500 ft. and upwards.

FIG. 155A—TAPER ADJUSTING OR GIB STRIP

There are many types of guiding strips and inclined adjusting strips, one or two of which are shown in Figs. 155A, B, C and D.

The Automatic Lathe

We have seen that a capstan lathe is in effect a centre lathe modified for the production of pieces by repetition, all the movements, motions, feeds and other necessary manipulations being incorporated for this purpose. Most of these operations are done by hand under the control of the capstan operator, but in an auto all the motions are performed automatically. The bar is fed up to the stop, the turret indexed round, the spindle speed changed or reversed when necessary as for thread cutting, the tools brought up and fed into the work and then retracted when the operation is completed, and finally the finished piece parted off, all these operations being performed automatically by

FIG. 155B

suitably designed cams, cam drums, clutches and the turret indexing mechanism.

In dealing with this subject, the principle of the automatic lathe will be

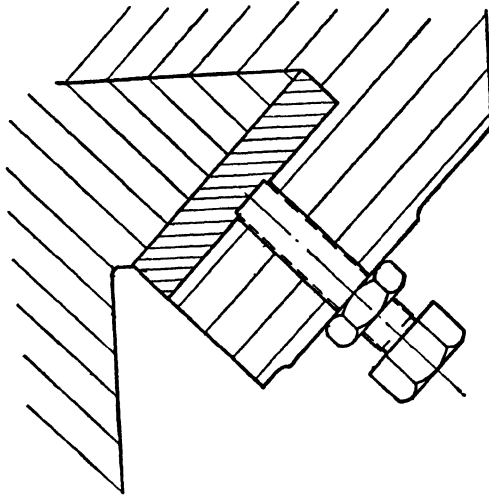



FIG. 155C

dealt with instead of giving a separate series of descriptions covering say automatic screw machines, semi-automatics, single-spindle autos, multi-spindle autos and chucking automatics. Each of the foregoing types

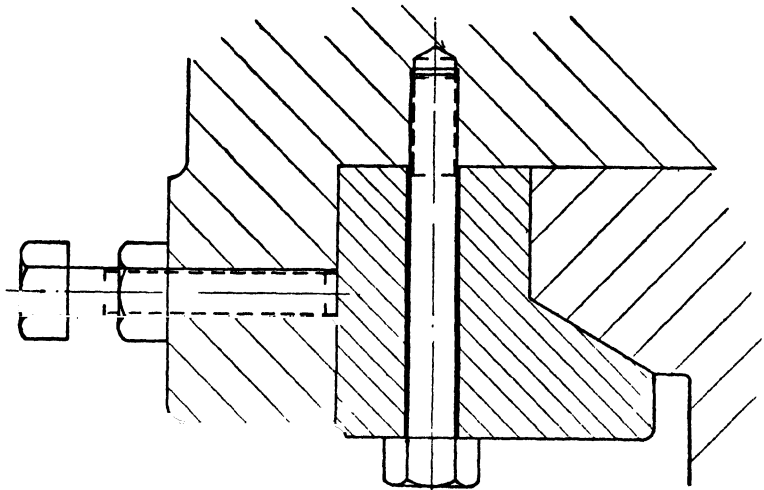



FIG. 155D—ADJUSTING STRIP FOR FLAT AND VEE WAYS

have many common points in the principle of their mode of operation, and can therefore be dealt with in the manner suggested. To discuss, each of these machines fully would take up far more space than can be allocated here.

By way of preamble, it might be noted that a skilful capstan operator can use the automatic feed for turret operations, such as roller-box turning, drilling and threading, and at the same time bring up the cross-slide tools and perform another operation. This considerably reduces the time required to complete a component, since in some cases two operations can be done at the same time, such as drilling and forming. In the automatic machine proper all the operations are performed auto-

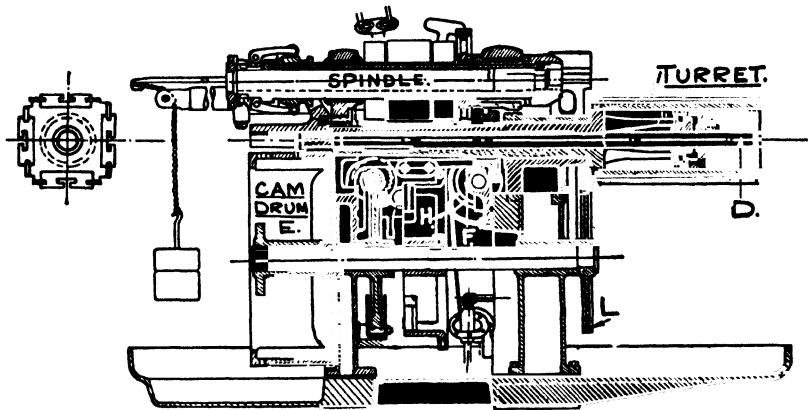



FIG. 156—EARLY-TYPE GRIDLEY AUTOMATIC MACHINE

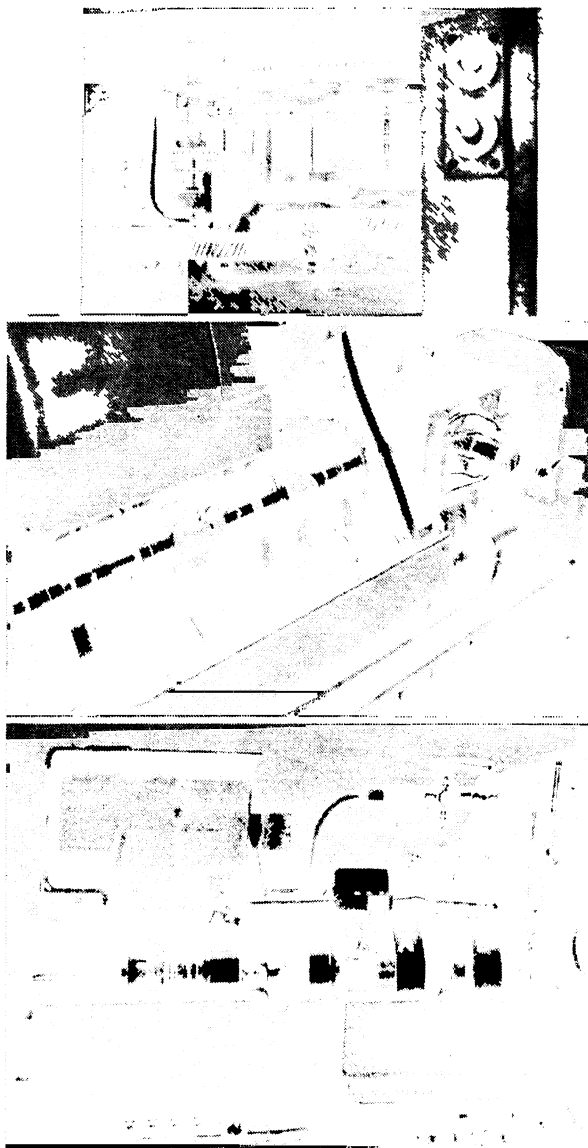
matically, and are laid out initially to allow for such overlapping as that mentioned. The early type, such as the Cleveland or Gridley, the latter being taken for illustration, had a cylindrical cam drum on which the various plate cams could be bolted, and these cams then controlled the movements of the tools in relation to the work. The turret, in this case a four-sided one as shown in the sketch (Fig. 156), is set below the work spindle and carries a number of toolholders depending on the requirements of the work in hand. This turret is sometimes set " off-square " to the work spindle, and each of the four faces carries an independent slide, which is operated from the cam drum *E* by bar *D*. The turret is indexed round by means of a wormgear *F*, which is brought into operation when the turret is unlocked by means of a lever *H*, which is controlled from a central cam drum by means of suitable dogs. A cam disc *L*, to the right of the other cams, operates the cross slide, and speed changes are effected by means of belt shift levers from the centre drum, as is the reversing of spindle rotation. The view in Fig. 156 makes the operation of this early-type machine clear.

Courtesy B S A Tools Ltd.

FIG 157—Top SPEED-CHANGE GEARS B S A AUTO
FIG 158—Centre BACKSHAFT, B S A AUTO
FIG 159—Bottom WORK-SPINDLE AND CLUTCHES

Naturally, the smaller sizes of the auto lathes are single-spindle machines, the turret being a circular unit with six stations operated by a turret-indexing mechanism in a vertical plane parallel to the work spindle. The motions of the turret tools when cutting are controlled by cams, but the advance and retracting of the turret up to the cutting position is performed by a separate unit working on a principle not unlike a capstan indexing mechanism but employing a Geneva motion. Briefly, the operation of an automatic screw machine is as follows:

The machine is driven from a motor located in the base of the machine under the headstock, the motor being mounted on a hinged plate, and transmits power to the work spindle through the fast-speed change gears and chain-driven sprocket, the work-spindle drive being through the rear of the two clutches on the spindle. Pick-off gears are used to vary

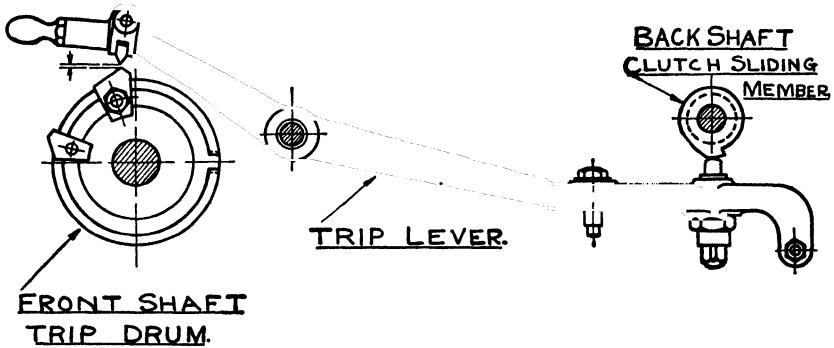



FIG. 160

the spindle speed, and these are shown on the right of the gearbox (Fig. 157).

The backshaft is driven by a belt at constant speed, and makes one complete revolution for each operation of the bar-feed mechanism and indexing of the turret.

In the B.S.A. machine the backshaft makes 120 r.p.m.:

$\therefore$ To feed stock takes $\frac{60}{120} = \frac{1}{2}$ sec.

Speed changes take $\frac{1}{2}$ revolution of backshaft $= \frac{60}{120 \times 2} = \frac{1}{4}$ sec.

Turret indexing takes 1 revolution of backshaft $= \frac{1}{2}$ sec.

On the backshaft are the clutches for controlling the various mechanisms which accomplish the idle movements, i.e. movements which are not actually operating on the work, such as feeding the bar to the stop, changing the speeds of the spindle or indexing the turret round. The backshaft is shown in Fig. 158, and the work-spindle drive and clutches in Fig. 159. From this backshaft the drive is taken through the cycle

time gears to a worm-reduction gear to the turret camshaft which carries the turret lead cam. From this turret camshaft the drive is continued

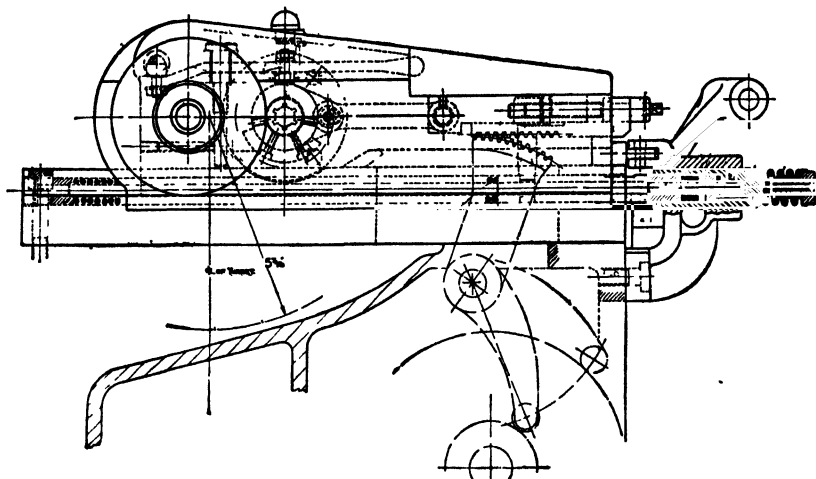



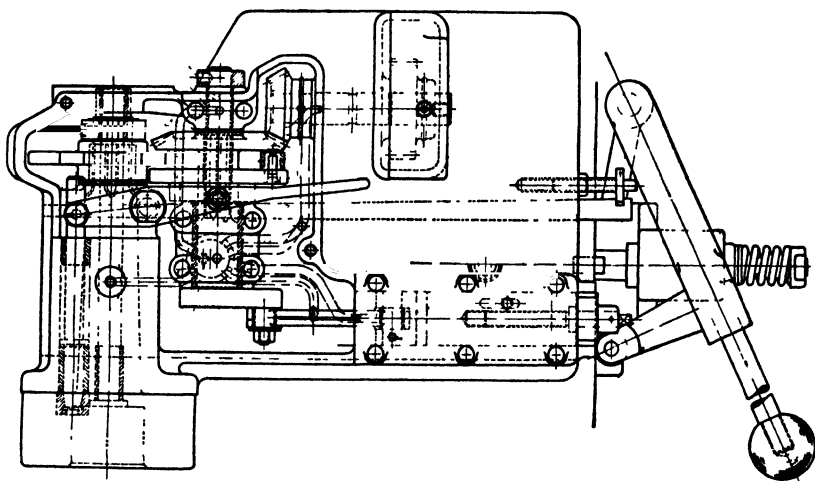
FIG. 161—ELEVATION OF TURRET INDEXING MECHANISM

Courtesy B.S.A. Tools Ltd.

FIG. 162—PLAN VIEW OF TURRET INDEXING MECHANISM OF B.S.A. SINGLE-SPINDLE AUTO

by means of a right-angled bevel drive, the bevel gears having an equal 1:1 ratio to the front camshaft. The front camshaft carries the cross-slide cams and the cam for the third or parting-off slide and also the trip drums, and these can be seen from the view in Fig. 166. The drums on the

front camshaft carry adjustable trips which connect to the backshaft by means of the trip levers that are shown in Fig. 160, and these levers extend through the body of the machine between the front and back shafts in order to operate the clutches carried by the latter.

The motions of the tools carried by the cross slides and turret are controlled by the cross-slide cams on the front shaft and the lead cam on the cross shaft at right angles to the front and backshafts.

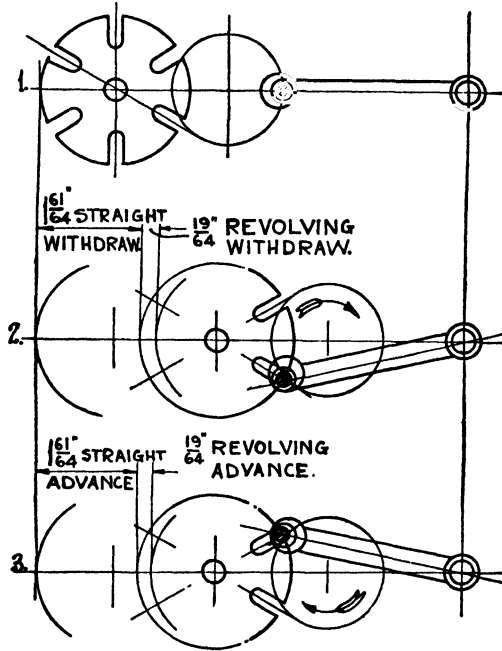
The turret slide is operated by a lever, one end of which has a roller

Courtesy B S.A. Tools Ltd.

FIG. 162A—TURRET INDEXING METHOD OF OPERATION

follower which engages the lead cam, and the other a segmental gear which meshes with the rack on the turret slide.

In a similar manner the cross slides are operated and the mechanism is indicated in Figs. 163 and 166. The return motion of the slides is obtained by spring pressure. The turret mechanism is shown in Figs. 161, 162, and 162A.

The Headstock and Work Spindle

The work spindle is mounted on heavy roller bearings at the front and opposed single-direction thrust bearings at the rear which are renewable when wear in service makes this advisable or necessary. The change-

speed clutches on the spindle are adjustable by means of rings *A* and *B* (see Fig. 159).

The collet which grips the bar can be adjusted, so that a desired grip of the collet on the bar is obtained, by means of the two nuts *C* and *D* (Fig. 159). Two cushion washers provide compensation for slight variations in the diameter of the bar stock used in the machine.

B.S.A. Single-spindle Automatic Lathe No. 68.—A general view of this machine is shown in Fig. 166, and other views have already been shown. Some of the mechanisms are as follows:

Cross Slides

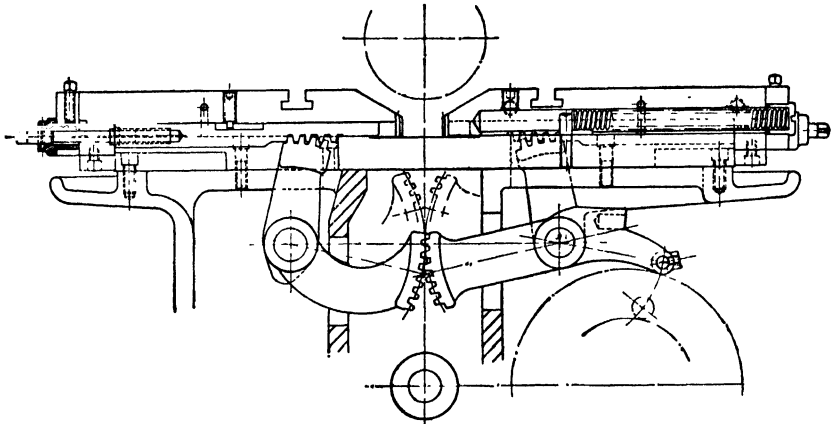
The mechanism for operating these is shown in Fig. 163, which is a section through the front and rear cross slides. The cam which operates

Courtesy B.S.A. Tools Ltd.

FIG. 163—FRONT AND REAR CROSS SLIDE OPERATING MECHANISM

the slides is mounted on the front camshaft towards the left-hand end of the machine, and in general the two slides are operated separately by individual cams, one controlling the front slide and one the rear. In Fig. 163 the two slides are shown as operated from one cam via segmental gears which, by suitable arms, engage with the racks cut in the undersides of the two slides. The slides are fed forward by this mechanism against springs which are compressed and which provide the means of returning the slides to the start positions.

Third or Vertical Cut-off Slide

A view of this slide is shown in Fig. 164, from which it will be seen that the motion required is transmitted from the cam on the front camshaft, through two arms with gear segments, to a push rod which actuates the slide through a lever.

The third slide is invariably used for parting off the work when finished, i.e. when all necessary operations have been completed.

Turret Indexing Mechanism

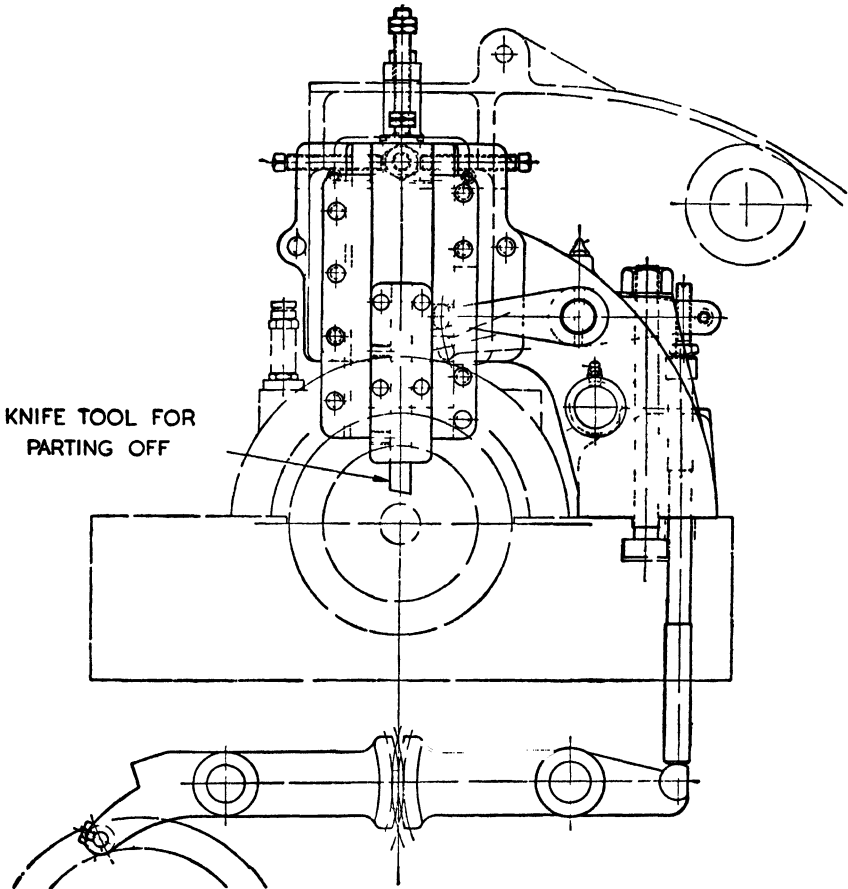
The turret indexing mechanism of the B.S.A. Single-spindle No. 68 Automatic Lathe is controlled from a cam drum on the front camshaft.

Courtesy B S A Tools Ltd.

FIG. 164—THIRD OR PARTING-OFF SLIDE MECHANISM

On this drum trip dogs are located, and these trip dogs, being adjustable, can be set to trip the operating lever which connects the backshaft and so operate the clutch at the required moment The clutch on the backshaft when released by the lever (see Fig. 160) enables the backshaft to turn the turret indexing mechanism. The motion from the backshaft

Courtesy B.S.A Tools Ltd

FIG. 165—CYCLE TIME GEARS

Courtesy B.S.A Tools Ltd

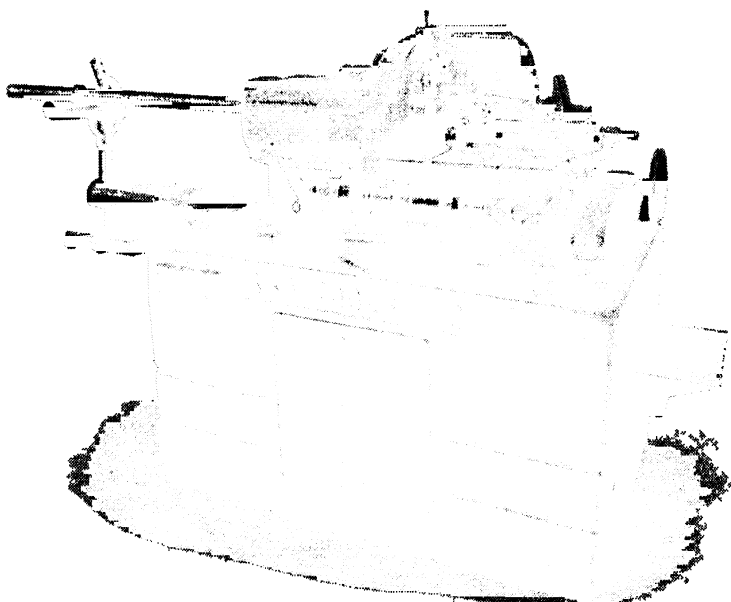



FIG. 166—GENERAL VIEW, SINGLE-SPINDLE AUTO

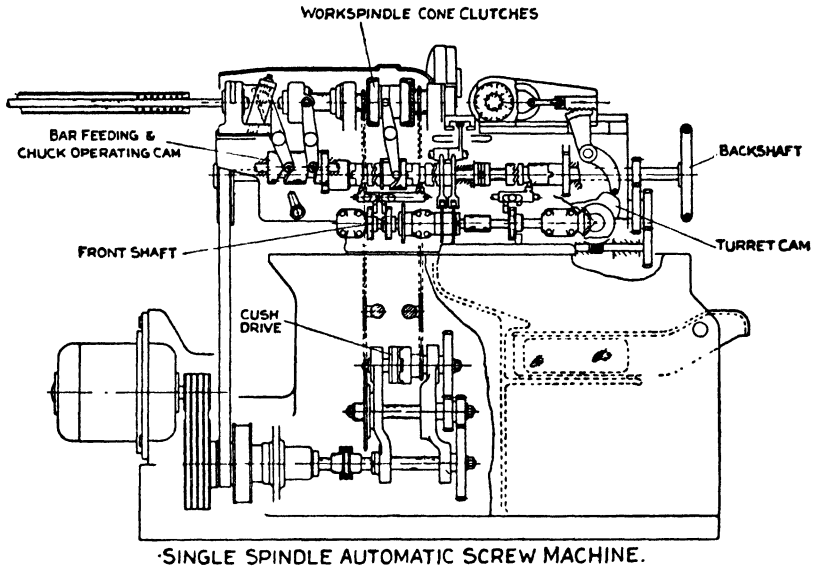
is transmitted to bevel wheels mounted on a splined shaft which also carries the indexing cam, and at the other end a crank and connecting rod is mounted. The connecting rod is fixed to the slide, and as the motion from the backshaft is transmitted to the bevel wheels, the shaft is rotated and the indexing cam also rotates, and as it does so it engages with a slotted plate mounted on the turret shaft, causing it to rotate through one-

Courtesy B.S.A. Tools Ltd.

FIG. 166A—OPERATING MECHANISM

sixth of a revolution. The connecting rod at the same time withdraws the turret and returns it to the beginning of the next stroke or operation with the new turret position in line with the work spindle. During this indexing operation the roller on the lead cam is swung out of contact, and is returned to the next lobe ready to advance the turret tool under the influence of the cam. A line diagram indicating the indexing of the turret is shown in Fig. 162A, and from this and the two views of the turret the indexing should be clear. The cycle time gears are shown in Fig. 165.

Cam Layout Sheet

As has already been indicated, the cams for the turret slide, cross slides, and third slide are drawn out and superimposed on one view in order that the complete cycle of operations which they control can be readily seen.

Such a cam layout sheet is indicated in Fig. 167, in which the lead cam profile is shown by a heavy full line, the front slide cam by a dotted line, and the rear slide cam by a chain dotted line.

Other machines have cam-operated motions, and in these the cams are located on a large cam drum. The Herbert No. 3A is such a machine, and the view in Fig. 168 clearly indicates the cams and the worm drive.

It will be seen that the setting up of the automatic is a lengthy and costly operation, and only considerable quantities of the same piece warrant this expenditure and yield a return. The making of a set of cams for each piece precludes the setting of the machine for small batches, and this was the state of affairs until the advent of " Wickman " Camless

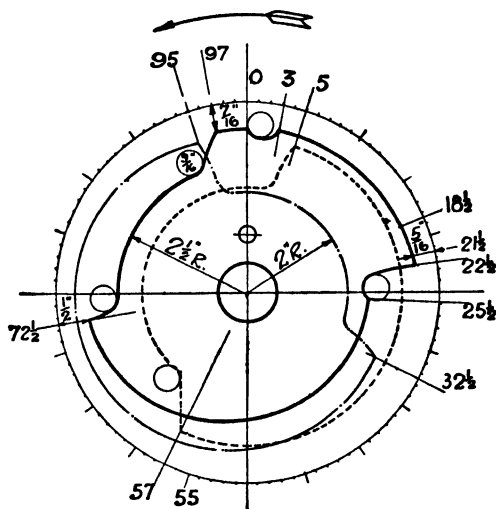



FIG. 167—CAM LAYOUT

Multi-spindle Automatics. In these machines many ingenious mechanisms are incorporated, of which the patented quadrant linkage is outstanding. In this quadrant linkage, simple sliding adjustments effect alterations in the longitudinal and cross-slide working strokes from zero to the maximum possible, whilst at the same time retaining unaltered the full fast approach of the tools. This dispenses entirely with costly cams, and reduces change-over times to a fraction of that formerly required, and provides an automatic equipment for short-run production. Thus these machines are easily and quickly set up, simple adjustments taking the place of the usual cam-changing operations.

In these machines five work spindles are provided and four cross slides

with individual working strokes which carry the form tools. The machine is made for bar work, models being $\frac{7}{8}$ in., $1\frac{3}{8}$ in., $1\frac{3}{4}$ in., and $2\frac{1}{4}$ in., and chucking machines for 5-in. and 6-in. capacity, and a general view of one of these machines is shown in Figs. 169(*a*) and 169(*b*).

To describe one of these machines in detail, including all the ingenious mechanisms, would be far too long a process for such a book as this, and attention is focused, therefore, on the main essentials.

"Wickman" Multi-spindle Automatic

Spindle

Five clutch-operated spindles made from high-tensile steel run in ball and roller bearings, and are indexed by an accelerated four-slot Geneva

Courtesy Alfred Herbert Ltd.

FIG. 168—CAMS AND CAM DRUMS, 3A HERBERT AUTO

motion designed to promote easy indexing by power or handwinding. These spindles are carried by an alloy-iron drum, and the general layout of the five spindles, drum, and ring gear will be appreciated from Fig. 170.

The work-spindle drum is located and clamped in position by a special toggle clamp acting against a rigid latch.

The indexing of the five work spindles is rapid, free from shock, and obtained from an accelerated four-slot Geneva plate whose motion is transmitted to the spindle drum by means of a gear fitted to the Geneva plate. Each spindle is driven by a driving gear *F*, which can be seen in

Courtesy A C Wickman Ltd

FIG 169—WICKMAN 5-SPINDLE AUTOMATIC LATHE

Fig. 171, showing the arrangement of the Wickman Multi-spindle Bar Machine :

A. Pressure disc.
B. Roller race to locate in bar-feed device.
C. Clutch body to locate in collet-opening mechanism.
D. Gear ring.
E. Thrust plate.
F. Spindle driving gear.
G. Drum-locking locating screws.
H. Dead-stop screws.

The arrangement is modified for the chucking machines, and this is shown in Fig. 172 :

A. Spindle-drive shaft.
B. Dead-stop screws.
C. Drum-locking locating screws.
D. Thrust plate.
E. Gear ring.
F. Spindle-clutch operating bobbin.
G. Air cylinder for operating chucks.
H. Pressure disc.

The chucks are opened and closed on the work by air pressure in cylinders *G*.

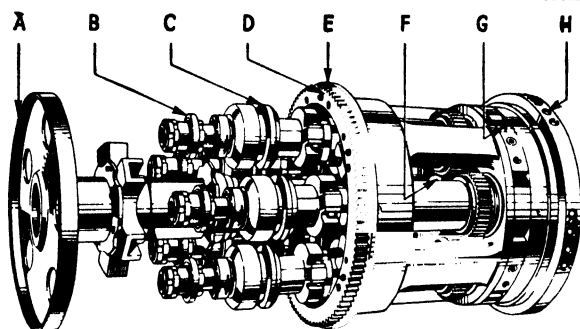
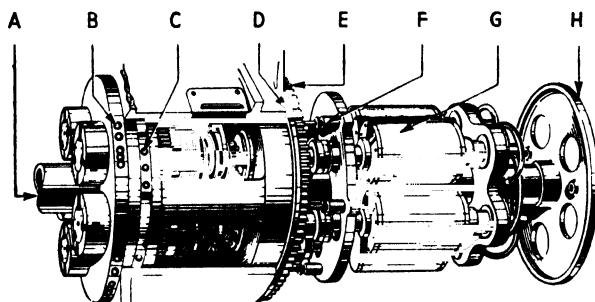
Cross Slides

The independent cross slides operate in spindle positions 1, 2, 3, and 4, and the cross slides have two distinct movements, feed motion and idle or return motion, actuated by two sets of fixed cams which are readily adjustable to give any desired feed stroke from zero to the maximum machine capacity. The fifth slide is fitted to bar machines, and this too is an independent cut-off slide for parting off ; it has its own cams which also operate the bar stop. Flat-form tools may be fitted to this slide to chamfer or form the end of the following component whilst parting off. Fig. 173 shows the fifth slide.

A fifth slide is not fitted to the chucking machines in order to leave a clear space for loading and unloading the work.

The cross-slide adjustment is shown in Fig. 174, and is effected by means of the nut, which is unlocked and the block moved into the required position on the graduated scale by sliding it in the Tee slot. This simple operation reduced change-over time to such an extent that the machine can be applied to batch work.

Centre Block

The main tool block or pentagon is in the centre of the machine, and carries the main end-working tools, such as those for turning and drilling,

Courtesy A C Wickman Ltd.

Work Spindles and Mechanism, Wickman 5-spindle Automatic Lathe

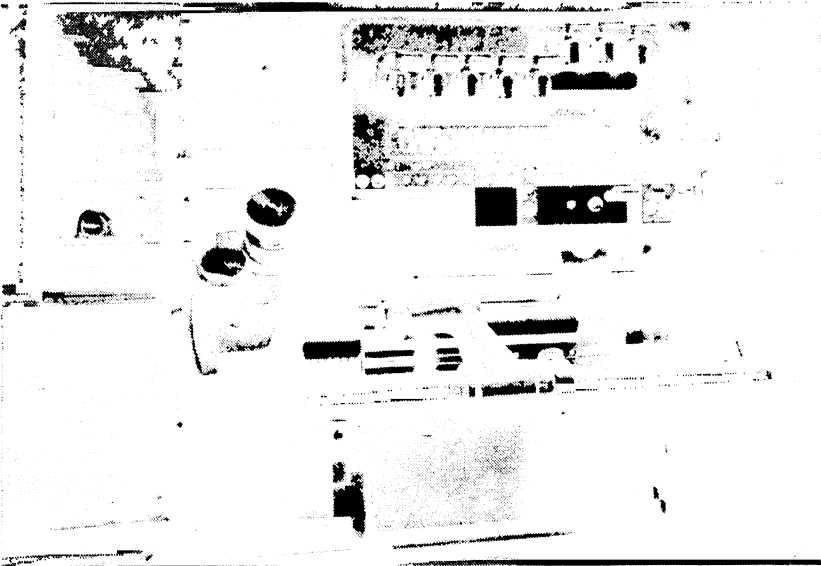



FIG 173—FIFTH SLIDE, WICKMAN AUTOMATIC LATHE

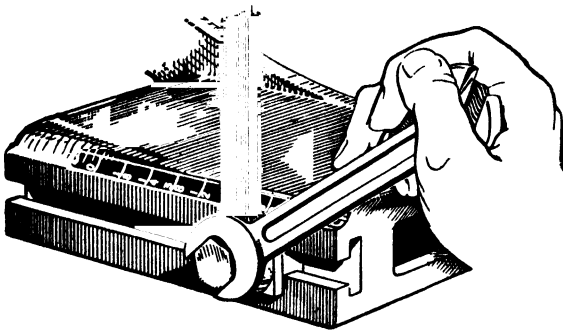



FIG 174—CROSS SLIDE ADJUSTMENT

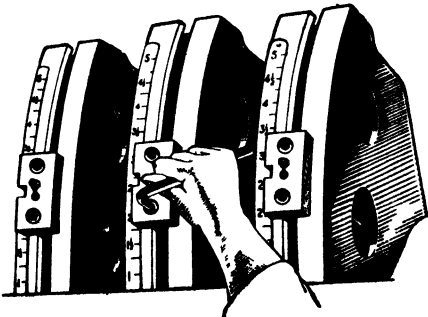



FIG 175—METHOD OF ADJUSTING FEED STROKES

Courtesy A C Wickman Ltd

and all tools set on it have the same feed. In the third and fourth positions are two independent slides whose feed strokes are set individually; these two, plus the feed obtainable on the pentagon, give three different feeds in the end or longitudinal position. The means of adjusting the feed strokes in the end or longitudinal position is shown in Fig. 175.

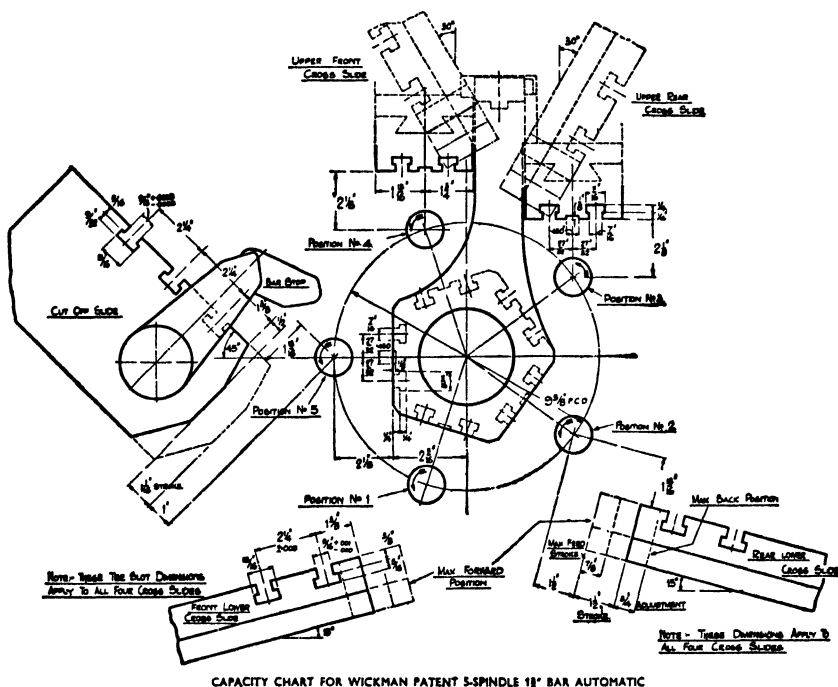
The centre block or pentagon is illustrated in Fig. 176, which is a

Courtesy A. C. Wickman Ltd.

FIG. 176—CENTRE BLOCK, WICKMAN 5-SPINDLE AUTO

capacity chart showing the cross slides and their positions, the view being an end elevation.

With the foregoing details in mind, it will now be possible to follow the tooling of the machine for a given job.

Referring to Fig. 176, it will be seen that at position 5 the finished part is being cut off by the parting-off tool in the fifth slide, and as already indicated, this slide controls the bar stop. At this position a new length of bar is fed forward, and then it is indexed to position 1, where the cross-slide tools and end tools on the centre block perform their operations on the bar. When these are completed, the head is indexed again, and the bar now moves to the second position and a new length is fed at 5. In

this manner the part moves round, coming under the influence of the tools in the slides and the corresponding faces of the pentagon, until the fifth slide is reached, at which point it is parted off. The following part is being finished at position 4, and will be parted off when a new length of bar has been fed through the collet at 5 and passed to the first operation tools at position 1. In the first place the tool layout must give the necessary tool clearances for the part in question to be machined at the various stages.

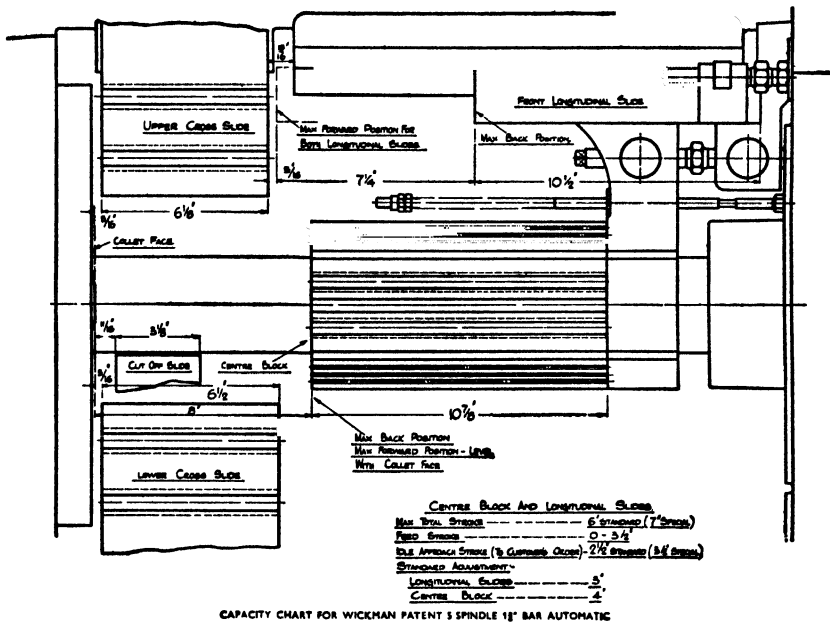
A longitudinal section of the capacity chart corresponding to Fig. 176

Courtesy A. C. Wickman Ltd.

Fig. 177—Centre Block

is shown in Fig. 177. The centre block and slides are shown in Fig. 178.

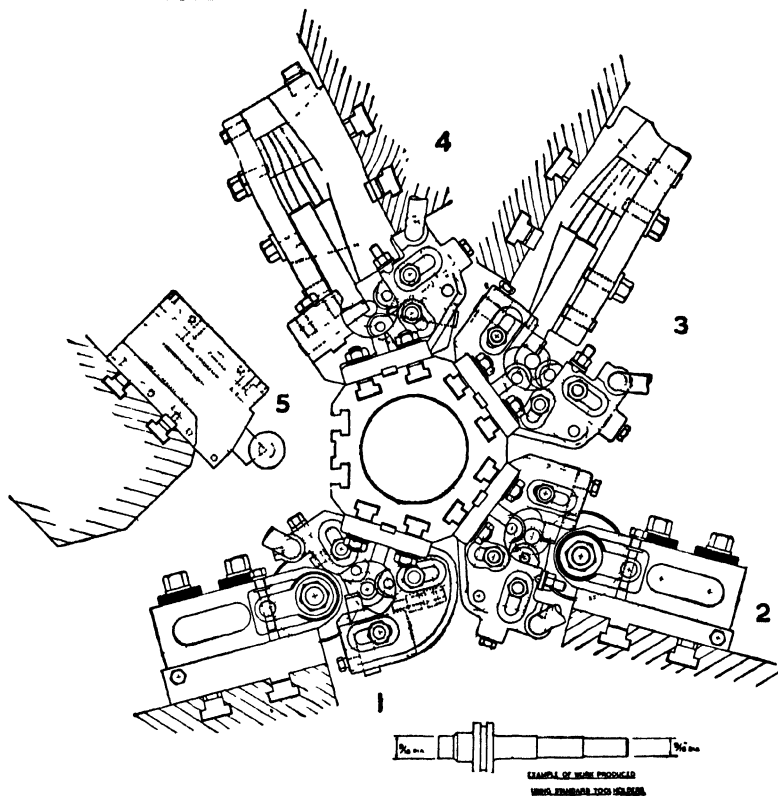
Illustrations of tool layouts and sequence of operations are given in Chapter V, and an interesting one is the water-tap spindle shown in Fig. 179. This component is made from manganese bronze in 5·4 sec. on the Wickman ⅞-in., 5-spindle auto, and a flat generator attachment cuts a square head on the spindle, an operation which would otherwise have to be done by milling at much greater length. This method employs the principle shown in Fig. 180, in which a cutter with half the number of sides to be produced on the workpiece is revolved at twice the speed, and the combination of these factors produces the flat sides. Two flat parallel sides with a single-point tool, a square with a two-

Courtesy A. C Wickman Ltd.

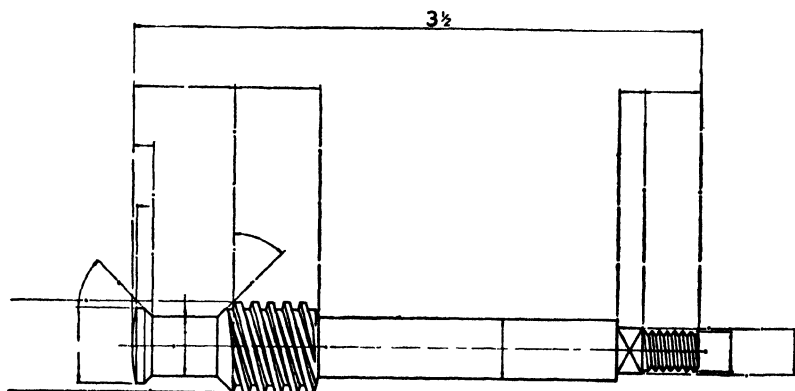
FIG. 178—CENTRE BLOCK AND SLIDES

Courtesy A. C. Wickman Ltd.

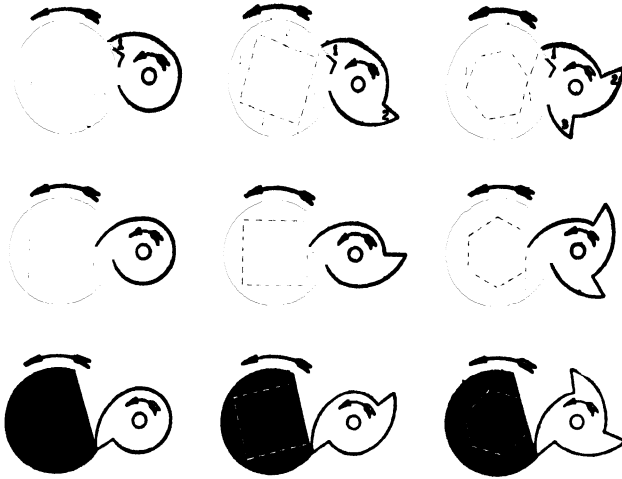
FIG. 179—WATER-TAP SPINDLE

Courtesy A. C. Wickman Ltd.

FIG. 180—GENERATION OF VARIOUS SHAPES BY TOOLS USED IN 5-SPINDLE AUTO

Courtesy A C Wickman Ltd

FIG. 181—FLAT-GENERATING ATTACHMENT, 5-SPINDLE AUTO

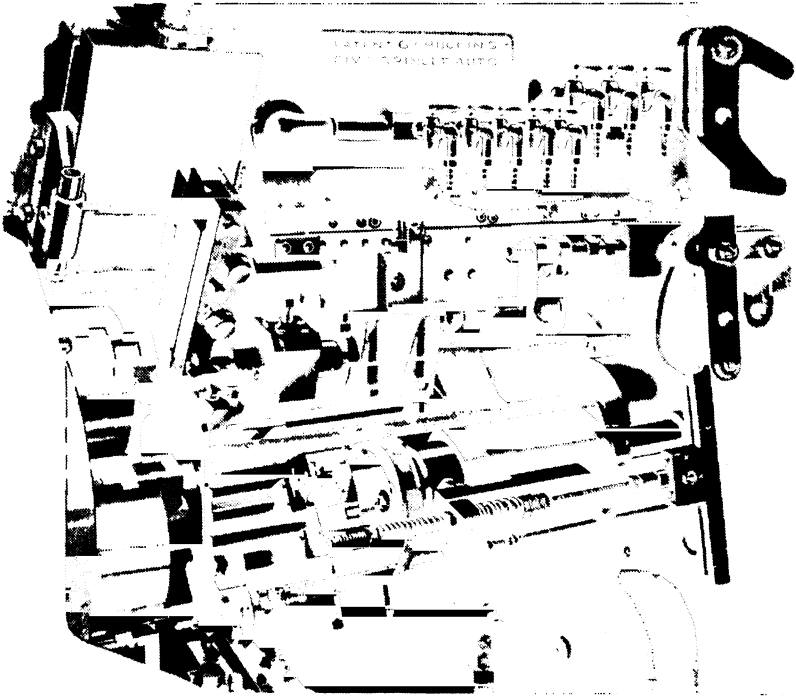
point cutter and a hexagon with a 3-blade cutter. A view of the attachment in operation is given in Fig. 181.

Courtesy A. C. Wickman Ltd.

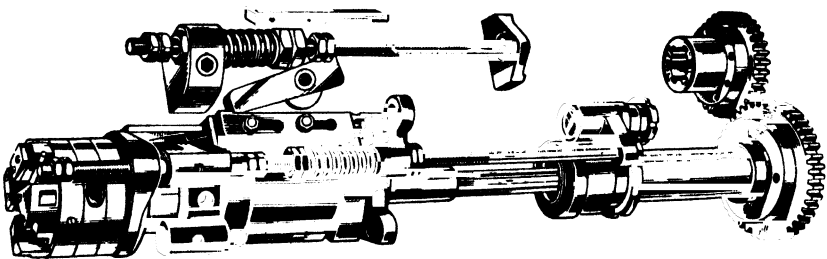
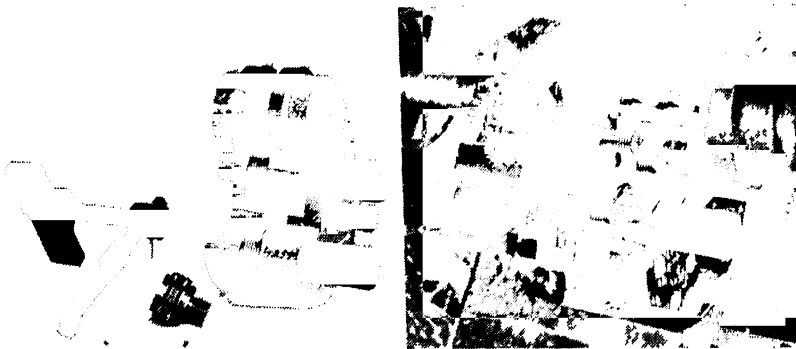
FIG. 182—REVOLVING DIEHEAD, 5-SPINDLE AUTO

Courtesy A. C. Wickman Ltd.

FIG. 183—DIEHEAD ATTACHMENT FOR 3RD AND 4TH POSITIONS

Screw threads are produced on work in these machines by various methods. Fig. 182 shows a revolving diehead.

For the steel component in Fig. 184, the external thread is rolled on

Courtesy A C Wickman Ltd

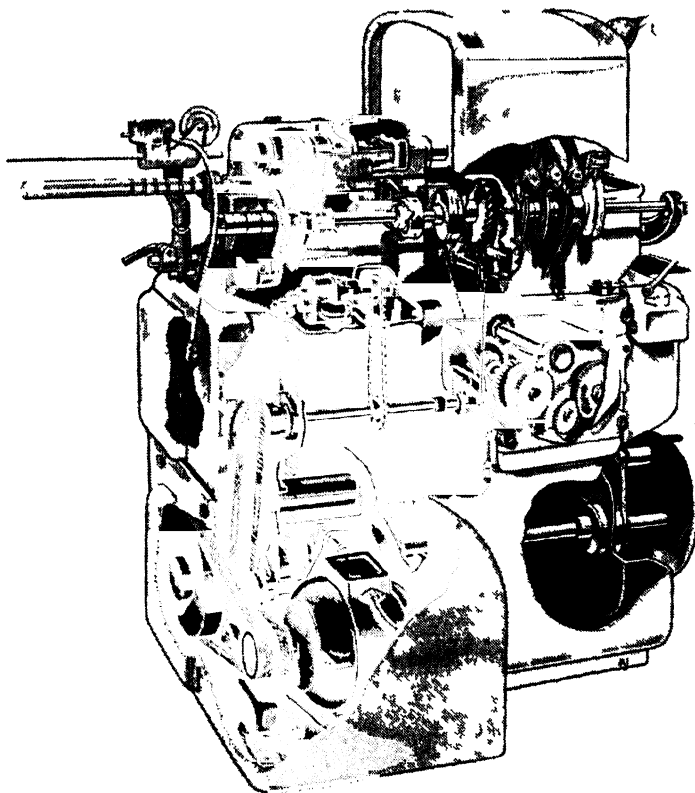
FIGS 184 and 185—THREAD-ROLLING ATTACHMENT

Courtesy A C Wickman Ltd

FIG 186—CUT-AWAY VIEW, SHOWING MECHANISM OF WICKMAN $\frac{3}{16}$-IN. PRECISION AUTOMATIC

by the thread-rolling attachment in the same illustration, and the attachment set in the machine is shown in Fig. 185 after completion of the operation on a component.

Wickman $\frac{7}{16}$-in. Precision Automatic

This machine is designed and built for the production of small, accurately finished parts from bar stock. It works with unequalled accuracy, finish, and concentricity on such components as precision screws, pinion blanks, and long slender work in one operation.

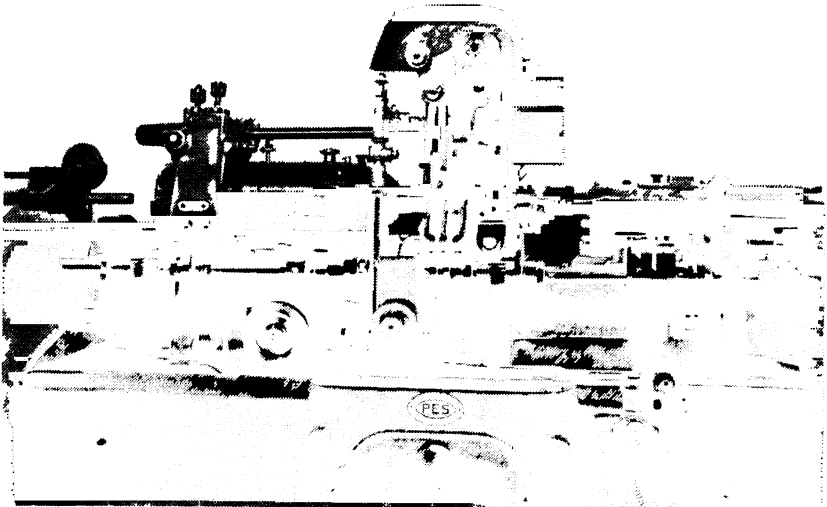
The machine is shown in Fig. 186, which is a cut-away diagram illus-

Courtesy A. C. Wickman Ltd

FIG. 187—WICKMAN $\frac{7}{16}$-IN. PRECISION AUTOMATIC

trating the various cams, gears and drives which actuate the various parts of the machine and control the tool movements. A general view of the machine is shown in Fig. 187, which is taken from an actual photograph.

The headstock of the machine is a sliding unit which travels on vee slides, the forward movement being obtained via a cam and return motion from spring pressure. A plate cam and bell-crank lever are used for headstock feeds up to $2\frac{1}{4}$ in., and a bell cam for feeds above $2\frac{1}{4}$ in. up to 4 in.

The maximum collet capacity is $\frac{1}{2}$-in. diameter for brass and aluminium, $\frac{1}{2}$ in. and $\frac{7}{16}$ in. diameter for steel. There are 84 spindle speeds, from 1,068 to 7,600 r.p.m., with a maximum spindle speed of 10,680 r.p.m.

The tool head is shown in Fig. 188, which is a front view indicating the five individually cam-fed tool holders which run in hardened and ground slideways, each tool holder being provided with a quick tool clamping device and fine adjustment for setting the tool on centre. There is also individual micrometer adjustment both radially and along the axis of the work.

A rear view of the tool head is shown in Fig. 189, and from these two

Courtesy A. C. Wickman Ltd.

FIG. 188—TOOL HEAD, FRONT VIEW, WICKMAN $\frac{7}{16}$-IN. AUTO

views the micrometers for the radial adjustment of each tool holder located at the upper end, and also the micrometers for the axial adjustment, can be clearly seen.

Another notable feature applicable to this machine is the three-spindle attachment. This combines in one unit the work of three spindles and can be used for centring, drilling, reaming, threading, and tapping. The unit is indexed from one spindle station to the next by two plate-type cams. This is shown in Fig. 190, in which the three spindles can be seen, also the cams for providing the tool movement and indexing.

Types of work produced on this machine are the star wheel pinion and vent plug shown in Figs. 191(A) and (B).

There are also special lathes which are used for work of specific nature, such as Profile Turning Lathes.

Scrivener No. 1 Profile Turning Lathe

A general view of this machine is shown in Fig. 192. It is generally used for turning automobile camshafts, the work being produced in the manner shown in Figs 192 and 192A. A master cam *B* at the back of the machine transmits the motion to roller *D*, held in a bracket on the tool slide. The slide takes the tool *C* to the work as shown, and the tool

Courtesy A. C. Wickman Ltd

FIG. 189—TOOL HEAD, REAR VIEW, WICKMAN $\frac{7}{16}$-IN. AUTO

continues cutting and reproduces the form on the master cam, the spring and thrust pin keeping the roller pressed against the face of the master cam. Thus it can be seen that a succession of tools arranged side by side can reproduce a complete camshaft, and these profile turning machines are set up for such work, turning the twelve cams on a 6-cylinder engine camshaft.

Whilst many of these machines are set up for camshaft work and are generally known as camshaft turning lathes, they are nevertheless capable of producing other shapes and profiles.

A set of typical profiles which are produced by the Scrivener profile turning lathe is shown in Fig. 192B, from which the scope of the machine can be visualised.

Form Relief

It is assumed that the student is already familiar with the standard types of cutters to which form relief is applied. When form relieving, the cutter blank, which has been previously gashed on a milling machine using a dividing head for the divisions according to the number of teeth in the cutter, is mounted on a mandrel between centres. A cutting tool, formed to produce the desired contour, is mounted in the tool holder of

FIG. 190—THREE-SPINDLE ATTACHMENT, WICKMAN $\frac{7}{16}$-IN. SINGLE-SPINDLE AUTO

the relieving slide of the lathe, and as the cutter rotates, the relieving cross slide moves towards the centre of the lathe. The inward movement of the tool is timed to start a little before the actual cutting commences, so that the relieving tool approaches the cut with the correct relative motion, and does not meet the work with a condition approaching shock load, as would be the case if the tool came in at the exact time the cutter tooth met the tool. The inward movement of the tool continues until the rotation of the cutter brings another tooth space or gash opposite the cutting edges, when it rapidly withdraws under the reaction of spring

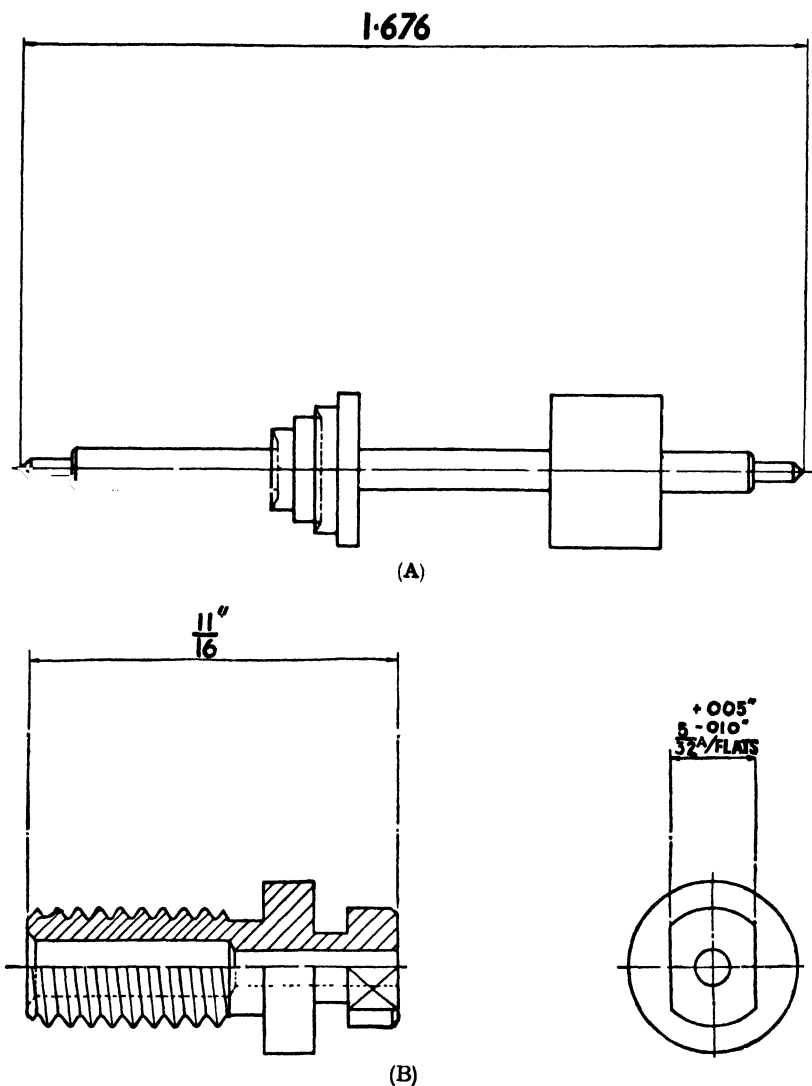
pressure *to its initial position relative to the centre line of the blank.* This relative motion of the tool and work results in the production of an

Courtesy A. C. Wickman Ltd.

FIG. 191—(A) ABOVE, STAR WHEEL; (B) VENT PLUG

eccentric form relief, a circumferential relief at the back of the cutting edges of the cutter teeth, a spiral form being imparted to the teeth by a

succession of cuts. The general points relating to the conditions are shown in Fig. 193 where D = Cutter diameter in inches

N = Number of teeth.

C = Cam throw (inward movement of relieving slide).

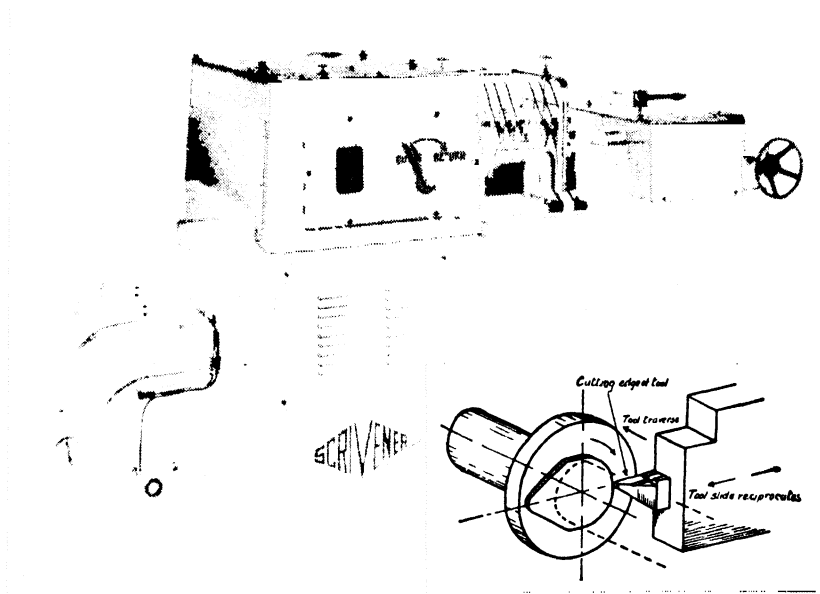
It should be noted that in the return movement indicated the tool inward movement commences prior to actual cutting, this being necessary to ensure a clean approach at the start of the cut.

Courtesy Arthur Scrivener Ltd

FIG. 192—PROFILE TURNING LATHE

The Relieving Curve

Referring now to Fig. 194, this shows a cutter having circumferential relief and radially gashed teeth, the radial profile of the cutting edge lying in the plane $R1$, and being repeated continuously in the successive planes $R2$, $R3$, $R4$, etc. Thus the necessity for constant contour is satisfied when the clearance angles θ_1, θ_2, θ_3, etc., between the tangents to the cutter radii T_1, T_2, T_3, etc., and the tangents T_{R1}, T_{R2}, T_{R3}, etc., to the relieving curve also remain constant. This condition is fulfilled when correct relief is applied to the cutter; it is clear that this determines and fixes the relieving curve, and obviously the degree to which these conditions are met depends on the form of the relieving curve.

To obtain the relieving curve a cam is used, and the relative movement between the relieving cutter and the work generates this curve, since it follows that the inward movement of the cutter in the cross slide is the deciding factor in determining the relieving curve.

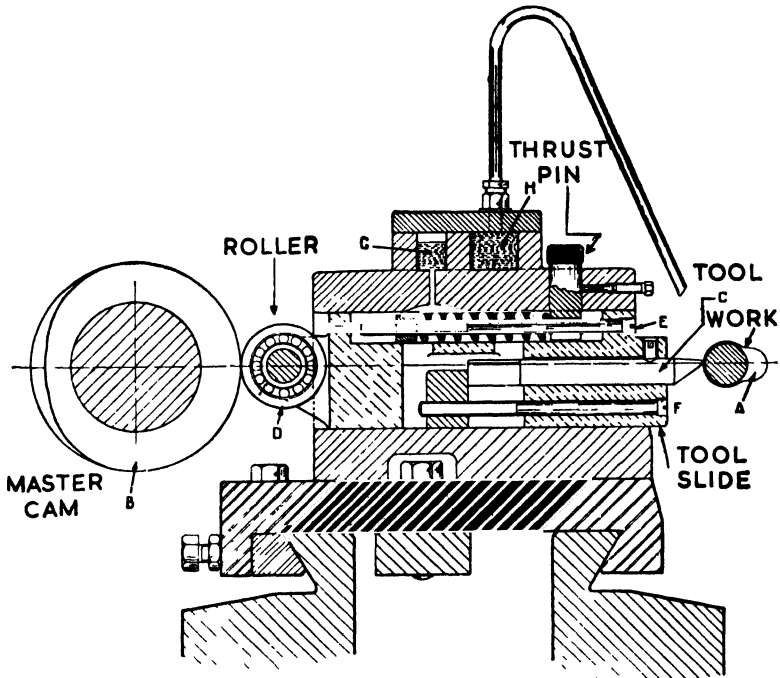
As already indicated, the reciprocation of the cross slide is determined by a cam which engages the cross slide directly or through some intermediate gearing, and the return stroke is usually accomplished by spring

Courtesy Arthur Scrivener Ltd.

FIG. 192A—SECTION THROUGH PROFILE TURNING LATHE

pressure. By means of an intermediate gearing, the revolutions of the cam, and hence the reciprocations of the cross slide, are related to the revolutions of the spindle carrying the work to be relieved. Thus for a single-rise cam it will be geared to make one revolution for each tooth on the cutter, and for a cutter having 10 teeth, a single-rise cam would have to make 10 revolutions to each turn of the cutter on the work spindle.

However, multi-rise cams are often used, and in some instances the number of rises or lobes on the cam may correspond to the number of teeth in the cutter, and in such a case the cam will make one revolution to one revolution of the cutter, that is to say, the cam driving the relieving

slides rotates at the same speed as the work spindle. When the number of rises does not correspond with the number of teeth on the cutter, the cam must be geared to rotate in the correct ratio, e.g. for a 16-tooth cutter and a 4-rise cam, the cam will rotate at 4 times the speed of the work. Similarly, for a quadruple cam relieving a 12-tooth cutter, the cutter spindle will rotate at one-third the rate of the cam speed, the gear ratio between the camshaft and spindle being 3 : 1, and the intermediate gears will be set to give these conditions.

Courtesy Arthur Scrivener Ltd.

FIG. 192B—TYPICAL PROFILES PRODUCED ON PROFILE TURNING LATHE

Since the inward feed of the cross slide relative to the rotary movement of the cutter blank is directly controlled by the cam rotation, it follows that the form of the relieving curve is determined by the contour of the cam. This contour takes the form of an accurately generated spiral. In the *logarithmic* spiral, the ratio of the lengths of consecutive radii enclosing equal angles is constant (i.e. the lengths form a geometric series or G.P.), and the angle which a tangent makes at any point with the radius at that point is constant. If now the cam has a contour of a logarithmic spiral, it follows that since it is geared to rotate at constant speed and in a fixed ratio to the spindle, it will produce a relieving curve with identical properties,

FIG. 193—FORM RELIEVING. RELATIVE MOTION OF TOOL AND CUTTER

i.e. a part logarithmic spiral curve with a constant contour, and therefore constant cutting angles.

However, the logarithmic spiral is not always used in practice, being difficult to produce, and a spiral with lengths as mentioned above but in an arithmetical series (i.e. A.P.) is found to be near enough for small

pitches, and an archimedean spiral is used which gives the arithmetical progression.

From Fig. 195 it will be seen that the spiral is produced by dividing

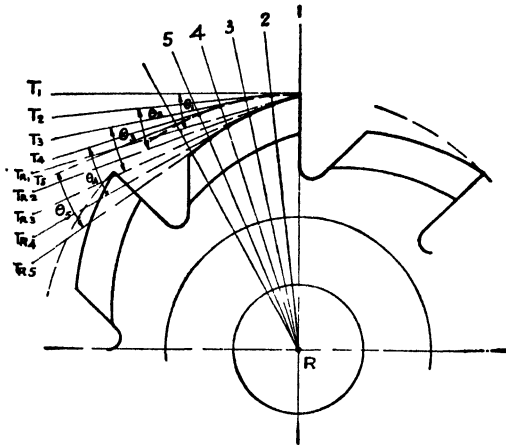



FIG. 194—THEORY UNDERLYING FORM RELIEF

the given distance into equal divisions and co-relating these with equal angular divisions. Referring to Fig. 195, point 1 on the straight line is

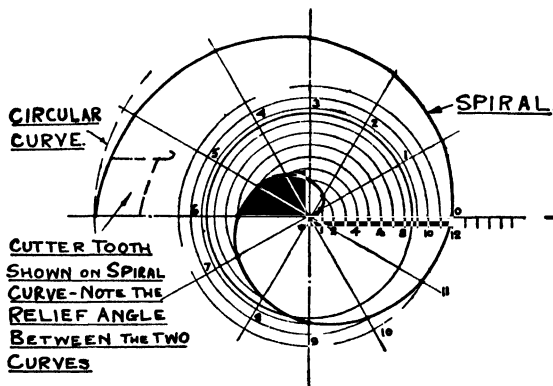



FIG. 195—ARCHIMEDEAN SPIRAL

swung round to intersect the radial line 1 and point 2 similarly swung round to meet line 2, and by completing this process for all the divisions, and then drawing a curve through the points thus obtained, the spiral required is arrived at.

From Fig. 193 it will be seen that the approximate relief angle is equivalent to :

$$\tan A = \frac{CN}{\pi D}, \text{ from } \frac{C}{\frac{\pi D}{N}}$$

where,

A = Relief angle.
C = Cam throw.
D = Cutter diameter.
N = Number of teeth on cutter.

Form relief is sometimes given in millimetres, and it is therefore necessary to convert the cam throw to millimetres, in which case, we get :

$$\tan A = \frac{C \, . \, N}{25{\cdot}4 \pi D} = \frac{CN}{80D}$$

If now the value of the desired angle of relief be inserted in the above expression, the cam throw required to produce such relief angle will be obtained, e.g. :

Find the cam throw necessary to produce a relief angle of 8°.

$$\tan 8° = \frac{CN}{80D}$$

i.e. $$80D \times 0{\cdot}1405 = CN$$

$$\therefore \text{Cam throw} = \frac{11{\cdot}24D}{N}$$

If the cutter is 3 in. diameter and has 10 teeth, the value of C is then :

$$C = \frac{11{\cdot}24 \times 3}{10} = \frac{33{\cdot}72}{10} = 3{\cdot}372$$

i.e. Cam throw = **3·372 mm.**

From the foregoing it will be seen that the circumferential relief angle produced on a formed cutter by a given cam throw varies with the diameter, i.e. the angle of relief varies with the variation in the diameter of the contour, the relief angle being greatest at the smallest diameter of contour. This is so because the relieving movement is constant, whereas the circumference varies with the diameter, becoming greater as the diameter increases and therefore making the angle smaller.

The formula given is constant for any given value of D, and if the minimum relief angle on the portion of the contour at the greatest diameter

is determined, *then the relief angle at any other diameter can be found.* By this means a check on the contour can be obtained.

For a cutter having angular sides, the relief angles are found as follows. The actual cam throw with reference to the plane of rotation of any point P (see Fig. 196) along the angular portion of the profile *normal* to the profile is equal to the cam throw sin $\theta°$, where θ is the angle of inclination of the slant side of the cutter.

The angle of normal relief measured about the same point will then be:

$$\tan B = \frac{C \sin \theta \times N}{80D} \text{ (using millimetres)}$$

$$\text{or } \tan B = \frac{NC \sin \theta}{\pi D} \text{ (using inches)}$$

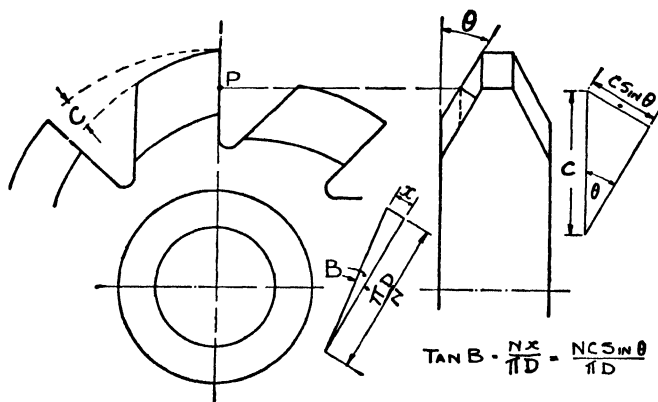



FIG. 196—FORM RELIEF ON CUTTER WITH INCLINED SIDES

In some cases a cutter has side relief in order to avoid rubbing, and in Fig. 197 we have conditions similar to the last case, but in addition a side relief to consider, which modifies the conditions governing the relief angle.

When a cutter is required with side relief (usually on one side only), the reciprocating slide is swivelled round away from the normal to the spindle and cutter axis in order to give the relieving tool a lateral movement in the direction in which the side relief is required.

The actual radial movement in this case becomes less than the cam throw, and obviously the amount by which the cross slide is swivelled round depends on the relief required. If the angle of swivel of the cross slide is ϕ, then the actual radial movement of the cam becomes $C \cos \phi = C_R$, the radial cam throw, the symbols being the same as those

for previous cases. The actual movement required to produce a given circumferential relief angle will be:

$$C = \frac{\pi D \tan A}{N \cos \phi}$$

from $\tan A = \frac{CN}{\pi D}$. i.e. $C = \frac{\pi D \tan A}{N}$ modified according to the angle of set over, ϕ.

Referring to the parts in Fig. 197, it will be seen that the actual effect of the cam throw with reference to the plane of rotation of any point on the angular portion of the profile, expressed in terms of a linear measurement normal to the profile, is equivalent to the clearance produced by

FIG. 197—INCLINED SIDE CUTTER WITH SIDE RELIEF

the actual radial movement of the cross slide plus an additional clearance resulting from the lateral movement of the cross slide. This can be given as follows:

First, actual cam throw C is modified to radial cam throw C_R by the setting over of the cross slide to an angle ϕ.

$$\text{i.e. } C_R = C \cos \phi.$$

This movement C_R, as shown in the sketch, is represented by a vertical line, the hypotenuse of a triangle the base of which is parallel to the side of the form on the cutter teeth and the perpendicular being part of the base of the triangle which represents the normal relief angle. This perpendicular is clearly equal to $C_R \sin \theta$. To this is added a further amount due to the side relief, and this extra portion is $L \cos \theta$. Thus the base of the relief angle triangle is:

$$C_R \sin \theta + L \cos \theta \quad . \quad . \quad . \quad . \quad (1)$$

Now $C_R = C \cos \phi$, and from the sketch (Fig. 197) it will be seen that the length L is equal to $C \sin \phi$, and substituting:

$$L = C \sin \phi$$
$$C_R = C \cos \phi$$

in equation (1) above, we get the base of the triangle E.

$$\therefore E = C \cos \phi \sin \theta + C \sin \phi \cos \theta$$
$$= C (\sin \theta \cos \phi + \cos \theta \sin \phi)$$

Now $\sin \theta \cos \phi + \cos \theta \sin \phi = \sin (\theta + \phi)$.

$$\therefore E = C \sin (\theta + \phi)$$

and the tangent of the normal relief angle J is given by:

$$\tan J = \frac{E}{\frac{\pi D}{N}} = \frac{NE}{\pi D}$$

$$\tan J = \frac{NC \sin (\theta + \phi)}{\pi D}$$

Summing up the results for convenience, we get:

Relief angle, $\tan A = \frac{CN}{\pi D}$, ordinary type form cutter (inches).

$\tan A = \frac{CN}{80D}$, ordinary type, millimetres.

Relief angle (normal),

$\tan B = \frac{NC \sin \theta}{\pi D}$, values in inches.

$\tan B = \frac{NC \sin \theta}{80D}$, values in millimetres.

$\tan J = \frac{NC \sin (\theta + \phi)}{\pi D}$, values in inches.

$\tan J = \frac{NC \sin (\theta + \phi)}{80D}$, values in millimetres.

When relief is being applied to a cutter by a relieving tool, rubbing cannot always be avoided, especially in cases where the contour of the teeth at the sides is nearly parallel; but this can sometimes be offset by increasing the cam throw. The amount of this relief is limited, however, because the amount of relief obtainable on the cutter is only about one-half that of the form tool producing the relief, since the effective clearance on the circumference of the cutter at any point is measured between the normal to the relieving curve and the normal to the cutter circle at that point. This will be clearly seen by reference to Fig. 198. In an actual

case of relieving, a formed cutter of the type indicated with a $\frac{5}{32}$-in. throw, 4-lobe cam, a relief angle of 10° was obtained. The clearance angle on the relieving tool was 20°.

Hob Relieving

To appreciate fully this procedure, let us suppose that the cutter which we have considered for form relief is now made much wider, and that it becomes in fact a number of narrow cutters side by side. The cutters are, in point of fact, a series of annular rows of teeth, but if, instead of this condition, we had the teeth spaced on a spiral or helix as in the case of a screw thread, then the relieving tool would have to have a lateral movement in order to keep in phase with the cutter teeth. The gashes are,

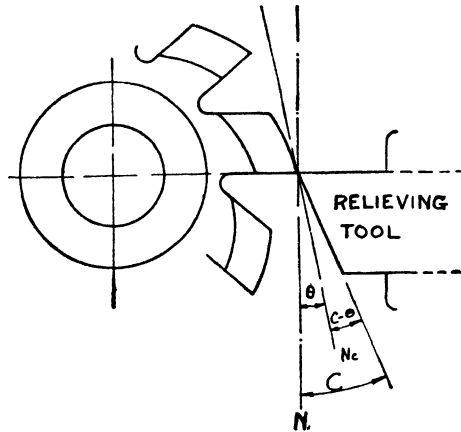



FIG. 198—REDUCTION OF CLEARANCE DUE TO CUTTER RELIEF ANGLE

however, still straight and parallel to the axis of the cutter, but suppose now the gashes were also made on a spiral path instead of a straight path, then the teeth would not only lie on a spiral in the transverse plane, but also on a helix in the longitudinal plane. Such is the case of the hob. Refer to Fig. 199, which shows the end view of a hob having 8 teeth, and incidentally 8 spiral flutes. Now, from the foregoing it will be clear that during one complete revolution of the cutter, the saddle and cross slide will travel laterally a distance equal to the *LEAD OF HOB* relative to the cutter, and that for one tooth, i.e. $\frac{1}{8}$ revolution, the lateral travel will be $\frac{1}{8}$ lead. If the flutes (gashes) were straight and the cam had 8 lobes, then $\frac{1}{8}$ revolution of the cam would result in the relief of one complete tooth *A* and the bringing of the relieving tool and cutter (hob) into relation for commencing relief for tooth *B*. The effect of the spiral gashes is, however, to displace or stagger the teeth, and the tooth *B*, following *A*, does not lie in a radial plane R_1, but in a plane R_2. The angular difference in the

spacing between successive teeth can be obtained from:

$$\text{Angular variation} = \frac{\text{Normal hob pitch} \times \text{cos of angle of spiral flute} \times 360}{\text{Lead of spiral gashes} \times \text{Number of gashes}}$$

$$= \frac{\text{Normal hob pitch} \times \text{Cos of angle of flute} \times 360}{\text{Lead of spiral} \times 8}$$

Similarly with the next tooth *C*, the angular variation of position with regard to the reference plane is twice as great in this instance, since the angular spacing is constant, i.e. $a_1 = a_2 = a_3$, where a = angular spacing of the hob teeth. It follows that the total angular variation for

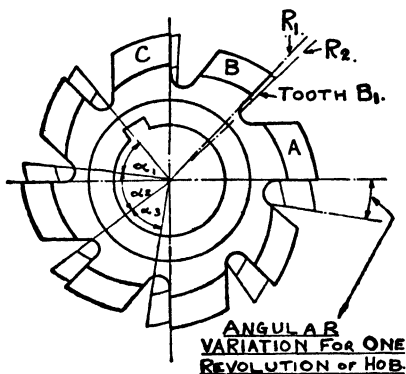



FIG. 199—END VIEW OF HOB SHOWING ANGULAR VARIATION

one revolution of the cutter relative to the reference plane will be given by:

$$\begin{matrix}\text{Total angular} \\ \text{variation}\end{matrix} = \frac{\text{Normal pitch of hob} \times \text{Cosine of spiral gash} \times 360}{\text{Lead of spiral gashes}}$$

In practice this variation is provided for by a compensation which creates a difference between the speed of the cutter and the cam driving shaft, such that the movement of the relieving tool relative to the cutter is either speeded up or retarded, depending on whether the spiral is right- or left-hand.

Assuming that the hand of the spiral is such that in the hob under consideration the teeth are in advance, as shown in Fig 199, the rate of the camshaft is speeded up relative to the hob a fraction of a revolution proportional to the angular variation in the tooth spacings. For example, if the spiral lead of the gashes in a hob is 50 in. and the lead of the hob is 1 in., the camshaft will make $1\frac{1}{50}$ revolutions to each revolution of cutter or work, provided that the number of rises on the cam is the same as the number of teeth, or rather the same as the number of spiral gashes. There are some cutters with annular rows of teeth and spiral gashes, and differing from a hob only in the absence of a lead on the teeth; in such

cases the angular variation is given by:

$$\frac{\text{Angular variation}}{\text{(Annular cutter)}} = \frac{\text{Pitch of cutter} \times 360}{\text{Lead of spiral gashes}}$$

As already stated, this extra movement of the cam relative to the work

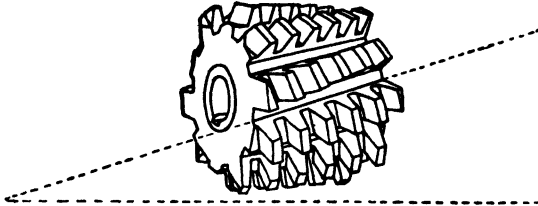



FIG. 200—HOB

is obtained by a train of compensating gears, and the gear ratio for this train is found thus:

$$\frac{\text{Number of teeth in drivers}}{\text{Number of teeth in driven}} = \frac{30 \times \text{Lead of thread}}{\text{Lead of spiral flute}}$$

Example.—Find the compensating gears necessary for relieving a hob having 2 in. lead of thread and a lead of spiral flute or gash of 18·75 in.

$$\frac{\text{Number of teeth in drivers}}{\text{Number of teeth in driven}} = \frac{30 \times 2}{18{\cdot}75} = \frac{90 \times 80}{75 \times 30}$$

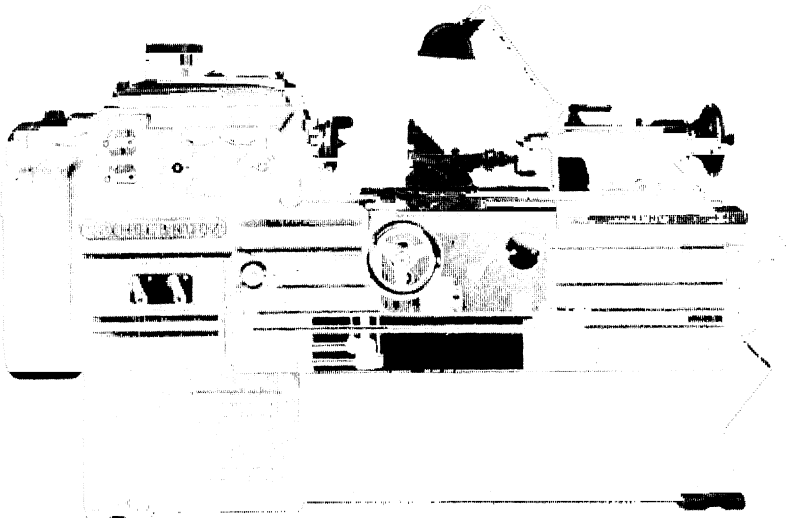
i.e. 90 drives 75 and 80 drives 30 wheel.

Courtesy Holbrook Machine Tool Co. Ltd

FIG. 201—UNIVERSAL RELIEVING LATHE

The Relieving Lathe

The " Holbrook " Model " R " No. 4 Universal Relieving Lathe is shown in Fig. 201, and schematic layout in Fig 201(*a*).

The mechanism of the lathe illustrated in Figs. 201 and 201(*a*) can briefly be described as follows.

The headstock provides 12 spindle speeds in geometric progression, see Chapter II, pp. 39–48, and with the relieving attachment a 6 : 1 speed reducer is used.

The relieving attachment includes two-4 rise cams one of $\frac{3}{32}$ in. throw and one of $\frac{5}{32}$ in. throw. When it is desired to relieve a normal type cutter the drive is taken to the cam via the spline shafts and gear box and worm and wheel from the gears giving the required number of jumps, i.e. N/n where N is the number of teeth in the cutter and n is the number of lobes on the cam. The drive from the headstock goes through a differential gear box set in neutral.

When a hob is to be relieved the angular variation due to the helix (spiral) angle of the flutes makes some compensation necessary. This is obtained through another set of gears called compensating gears and these are arranged to increase the speed of the cam with respect to that of the hob. To do this the differential gear box is engaged and the compensating gear train drives through the differential gear box and adds to the motion of gears N/n the extra motion necessary to compensate for the angular displacement resulting from the spiral flutes.

The compensating gears are driven from the reverse spindle under the

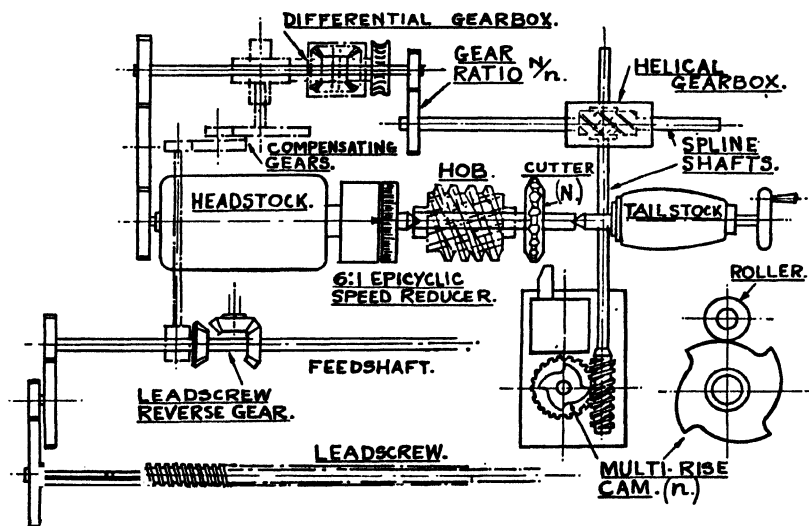



Fig. 201(*a*)

headstock and the drive is shown in Fig. 201 (*a*) in chain-dotted lines.

It should be noted that the throw or rise of cam required to provide a given relief can be obtained by the following method which should be compared with that shown on page 221.

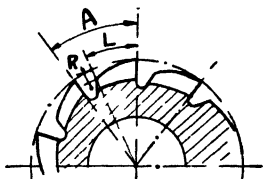



FIG 201(*b*)

Referring to Fig. 201 (*b*).

Let A = Angular distance from one flute to the next.
L = Angular distance of land required.
R = Relief required.
C = Cam throw or Cam rise.

$$\text{Then } C = R \times \frac{A}{L} = \frac{RA}{L}$$

$$\text{Now } A = \frac{\pi D}{N} \quad \therefore C = \frac{\pi DR}{NL}$$

Example: If the hob shown in Fig. 199 with 8 flutes has an angular distance of land of 25° and the relief per flute is 0·012 in.

$$\text{Then } C = \frac{RA}{L}$$

$$A = \frac{360}{8} = 45°$$

$$\therefore C = \frac{45}{25} \times \cdot 012 = \mathbf{0 \cdot 0216\ in.}$$

Sometimes the length of land is given as a percentage of the total distance between the flutes and in such a case the method is modified as shown by the following example.

Suppose $A = 100\%$ and $L = 40\%$ and $R = 0{\cdot}009$ in.

$$\text{Then } C = \frac{A \times R}{L} = \frac{100 \times \cdot 009}{40} = \frac{10}{4} \times \cdot 009 = \mathbf{0 \cdot 0225\ in.}$$

Single rise cams are recommended when the amount of relief is small and the number of flutes is below ten.

A view showing the relieving slide which is mounted on anti-friction bearings is indicated in Fig. 202.

Profile forming equipment can be bolted to the relieving slide, and an

example of this work, a formed cutter, is shown in Fig. 203.

For grinding relief on hobs, a disc-wheel head is incorporated, and a typical setup of this work is shown in Fig. 204.

Where the work has sharp relief, such as cutters, and hobs with excessive spiral angles, a pencil-wheel head is required. The grinding spindle runs at 22,400 r.p.m., and the setup is shown in Fig. 205. Relieving attachments can be fitted to suitable lathes, and an example

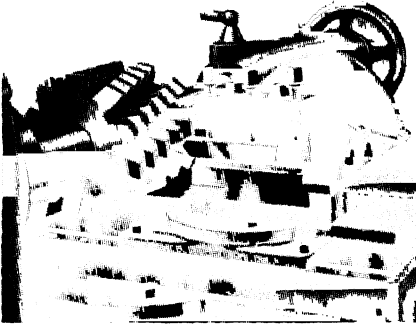



FIG 202—RELIEVING SLIDE

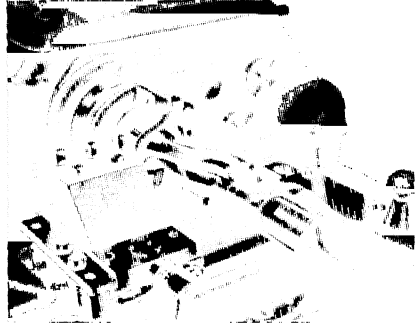



FIG 203—PROFILE-FORMING EQUIPMENT

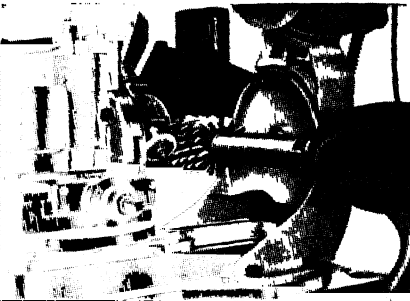



FIG 204—DISC-WHEEL HEAD

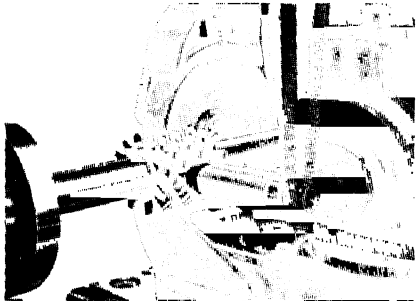



FIG 205—PENCIL-WHEEL HEAD

Courtesy Holbrook Machine Tool Co Ltd.

FIG. 206—RELIEVING ATTACHMENT

Courtesy Dean, Smith & Grace Ltd.

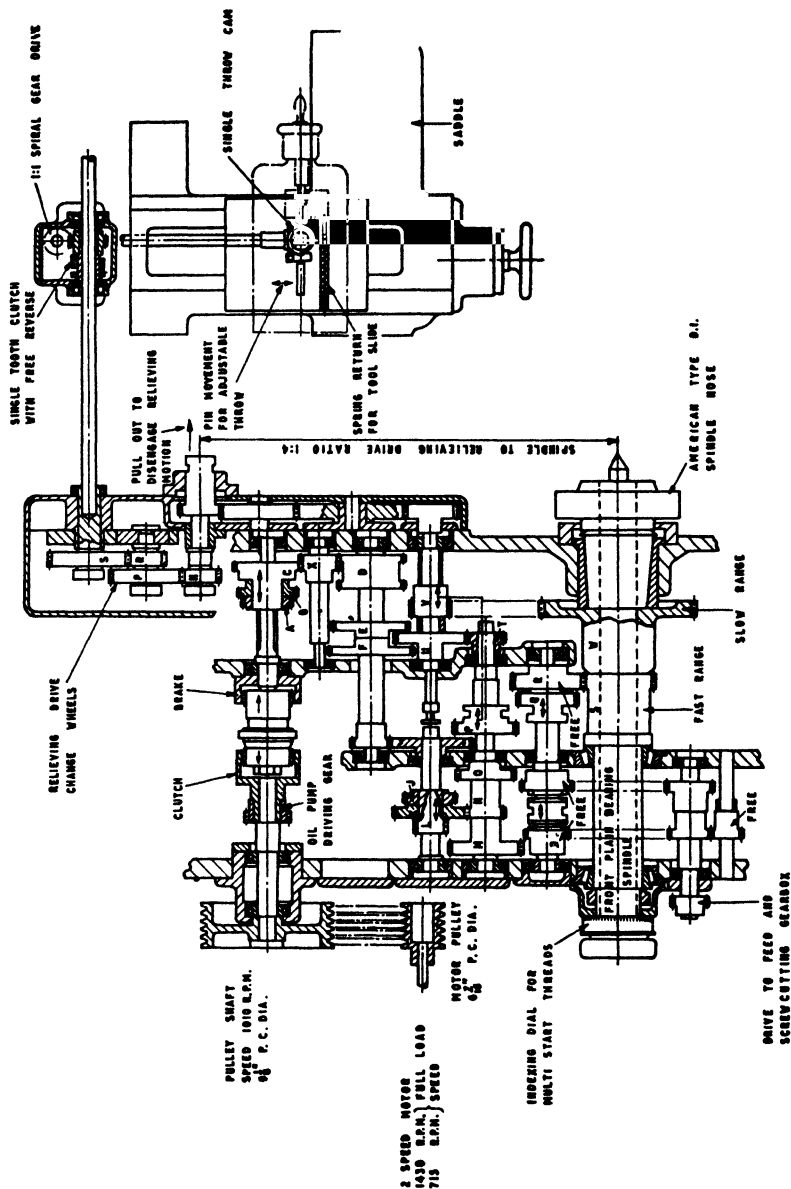



FIG. 206(*a*)—SCHEMATIC LAYOUT OF RELIEVING MECHANISM.

of such an attachment is shown in Fig. 206 illustrating relieving equipment.

One of the models of lathes made by the well-known firm of Dean, Smith and Grace Ltd., Keighley, Type 17T, a toolroom lathe with 17-in. swing, is fitted with a relieving mechanism.

Unlike the one already described, which for the most part uses a multi-rise cam and a sub-head in the form of a 6 : 1 epicyclic speed reducer, this machine uses a two speed motor and a single rise cam. The schematic diagram of the lathe is shown in Fig. 206(*a*), from which it can be seen that between the work spindle and the relieving drive there is a 1 : 4 gear ratio. This means that the cam makes 4 revolutions to one revolution of the work spindle and would in these conditions be suitable for relieving a 4-flute cutter such as a tap or similar.

For other flutes from 1 to 20 values of the gear trains for the change gears for the relieving motion are given in the following table:

TABLE OF GEARS

Change Gears for Relieving Motion (Straight Flutes)

No of flutes	*Change gears*				*Max Spindle RPM*	*No of flutes*	*Change gears*				*Max Spindle RPM*
	N	*P*	*R*	*S*			*N*	*P*	*R*	*S*	
1	35	60	30	70	72	10	60	30	50	40	6·9
2	30	50	inter	60	36	11	60	40	55	30	5·8
3	45	40	inter	60	24·5	12	70	35	60	40	5·8
4	60	40	30	45	18	13	65	40	60	30	5·8
5	50	45	inter	40	13·8	14	70	40	60	30	3·9
6	60	45	inter	40	11·7	15	70	28	60	40	3·9
7	70	35	inter	40	9	16	70	35	60	30	3·9
8	60	45	inter	30	9	18	70	35	63	28	3·9
9	70	35	45	40	7·8	20	70	30	60	28	3·9

Reference to Figs. 206(*a*), 206(*b*) and 206(*c*) showing the various layouts will enable the mechanism to be followed.

Starting with the electric motor, the pulley drive is via 5 vee belts to the input shaft, thence through the gears to the spindle. There are 36 forward speeds from 3·9 r.p.m. to 720 r.p.m. and 12 reverse speeds from 6·9 r.p.m. to 720 r.p.m.

The drive for the relieving mechanism is taken from one of the shafts in the headstock.

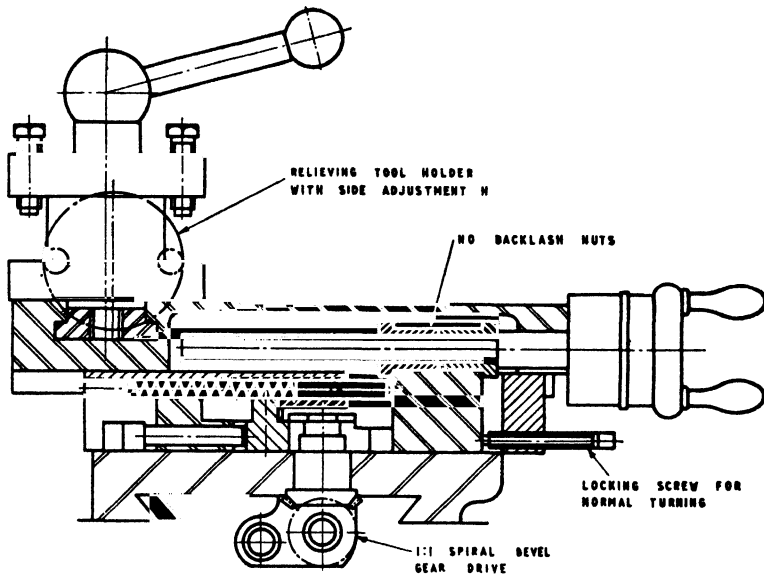
When it is desired to use the relieving unit the gear on the right-hand

Courtesy Dean, Smith & Grace Ltd.

FIG 206(*b*) -SECTIONAL VIEW OF RELIEVING SLIDE

end of the shaft carrying gear N is engaged with the drive from the head-stock as shown. The single throw cam is now driven via the change gears, N, P, R and S which will have been selected according to the number of flutes in the cutter being relieved. As will be seen, the drive from gear S is taken through a single tooth uni-directional clutch and a 1 : 1 spiral gear drive to the cross shaft. At the other end of this shaft carrying the 1 : 1 spiral gear drive is a 1 : 1 spiral bevel drive which engages with the actual cam shaft and thus drives the cam at the required speed.

The throw of the cam is adjustable within limits from a few thousandths of an inch to a maximum of $\frac{5}{16}$-in. by means of a set of 5 or 6 cams. The standard cam is the $\frac{3}{16}$-in. throw which can be adjusted to give $\frac{1}{8}$-in. throw on one hand and $\frac{1}{4}$-in. throw on the other, i.e. the $\frac{3}{16}$ in. can be reduced to $\frac{1}{8}$ in. or increased to $\frac{1}{4}$ in.

The method used to vary the throw of the cam is by a stroke adjuster which has a chamfer at one end and this is brought to bear on the block as shown in sketch (Fig. 206(*c*)).

The tool slide is returned by spring pressure after the cam has caused it to move forward to take a relieving cut on the work.

For a cutter with 12 straight flutes the change wheels required will be $N = 70T$, $P = 35T$, $R = 60T$, $S = 40T$, and with these fitted in the

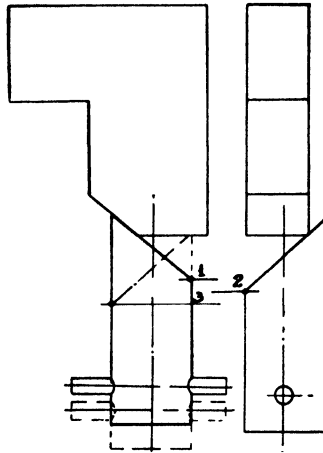



FIG. 206(c)

positions shown in the diagram the cam will be geared to give the relieving strokes required, i.e.

$$\frac{N}{P} \times \frac{R}{S} = \frac{70}{35} \times \frac{60}{40} = 3:1$$

This together with the 4 : 1 ratio between the relieving mechanism and the spindle gives $3 \times 4 = 12$, the number of flutes required.

Spiral Fluted Hobs

For relieving hobs and other cutters with spiral or helical flutes or gashes the change gears required must be calculated to compensate for the angular variation in the position of the teeth due to the helical flute. Thus the gears N, P, R, and S must be chosen to suit the number of flutes in the hob, but they must also accommodate the angular variation due to the helix angle of the flutes. See Figs. 199 and 200.

The gears required for this work are obtained from the following formula:

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{N(L + P)}{4L}$$ where N = number of flutes;
L = lead of spiral flute;
P = lead of hob.

For the hob shown in Fig. 199, i.e. with 8 flutes, if the lead of the hob is 1 in., and lead of spiral gashes 64 in., then

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{N(L + P)}{4L} = \frac{8(64 + 1)}{4 \times 64} = \frac{8 \times 65}{4 \times 64}$$

$$= \frac{2}{1} \times \frac{65}{64} = \frac{65}{32} = \frac{65}{40} \times \frac{75}{60} = \frac{65}{40} \times \frac{50}{40}$$

which is better since the $75T$ and $60T$ wheels are too large.

For the example of 12 flutes used in the earlier calculation, let the lead

of the hob, i.e. thread lead = ¾ in. and the lead of spiral = 24·88 in., then

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{N(L+P)}{4L} = \frac{12(24{\cdot}88 + {\cdot}75)}{4 \times 24{\cdot}88} = \frac{3 \times 25{\cdot}63}{24{\cdot}88}$$

$$= \frac{76{\cdot}89}{24{\cdot}88} = \frac{3{\cdot}090434}{1} = 3{\cdot}090434$$

Thus it will be seen that the gear ratio of 3 already found for the 12 straight flutes is now modified to 3·090434, the difference of ·090434 being the compensation required for the spiral lead, and the overall gear ratio will be 12·361736 instead of 12 as for straight flutes.

This ratio $\frac{3{\cdot}090434}{1}$ must now be extended to give a suitable combination of gears such as $\frac{68}{55} \times \frac{75}{30}$.

If now this combination is multiplied it will be seen that these gears give a ratio of $\frac{5100}{1650} = \frac{51}{16{\cdot}5} = 3{\cdot}089892$ and the difference is 0·000542.

Since the ratio for straight flutes is 3 and the compensation is ·090434 the error must be compared with this extension of ·090434. Expressed as a percentage error it gives ·006% in this instance which can well be accepted.

Gears for Spiral Flutes where Lead is not given

It might well be that a hob is sent for relieving and no details are given. It is easy to count the flutes and the hob or thread lead can be measured, but the lead of the spiral flutes is more difficult to obtain. It can, however, be found from the following formula

$$L = \frac{\pi^2 D^2}{P} = \frac{9{\cdot}87 D^2}{P}$$ where L = lead of spiral flute; P = lead of thread; D = pitch dia. of hob.

When L has been found from the above it can be used in the formula.

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{N(L+P)}{4L}$$

Example.—Hob with 15 flutes, lead of flutes unknown.
Lead of threads = 2⅝ in. 3 start hob. Pitch dia. = 4·878 in.

$$\text{lead of spiral } L = \frac{9{\cdot}87D^2}{P} = \frac{9{\cdot}87 \times 4{\cdot}878^2}{2{\cdot}625} = 89{\cdot}474 \text{ in.}$$

Substituting this value of L in the required formula we get

$$\frac{\text{Drivers}}{\text{Driven}} = \frac{N(L+P)}{4L} = \frac{15(89{\cdot}474 + 2{\cdot}625)}{4 \times 89{\cdot}474} = \frac{1381{\cdot}48}{357{\cdot}9}$$

If the gear ratio thus found is not in itself a suitable fraction it must be reduced or expanded to the nearest suitable fraction, in this case it is $\frac{1379{\cdot}4}{357{\cdot}5}$ and this gives a gear ratio of

$$\frac{66}{39} \times \frac{57}{25} = \frac{1254}{325} = \frac{N}{P} \times \frac{R}{S}.$$

It could happen that the gears obtained as a result of factorisation do not mesh correctly and it will be necessary to re-factorise or take another suitable fraction and from it calculate another set of gears.

The lead of a spiral corresponding to a given ratio can be found from

$$\text{Lead} = \frac{N \times P}{4R - N} \quad \begin{aligned} \text{where } N &= \text{number of flutes;} \\ P &= \text{lead of thread;} \\ R &= \text{change gear ratio.} \end{aligned}$$

Checking the above lead gives

$$\text{Lead} = \frac{15 \times 2{\cdot}625}{4 \times \frac{1254}{325} - 15} = \frac{39{\cdot}375}{{\cdot}43384} = 90{\cdot}76 \text{ in.}$$

See Fig. 206(*d*), which shows the disposition of the two leads.

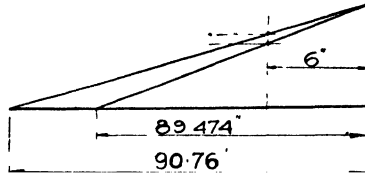



FIG. 206(*d*)

It will be clear that there is a difference of 0·286 in. between the two values 90·76 in. and 89·474 in. and if the hob flutes are cut to a lead of 90·76 in. the flute would be out of square to the lead of the thread, the amount of variation being found as follows:

$$\text{Tan. lead angle of thread} = \frac{\text{lead of thread}}{\pi \times \text{pitch dia.}} = \frac{2{\cdot}625}{3{\cdot}1416 \times 4{\cdot}878}$$

$$\text{Tan.} = {\cdot}171287, \text{ angle} = 9°43'$$

$$\text{Tan. spiral flute lead angle} = \frac{\text{pitch dia.} \times \pi}{\text{spiral lead}} = \frac{4{\cdot}878 \times 3{\cdot}1416}{90{\cdot}76}$$

$$= {\cdot}168853, \text{ angle} = 9°35'$$

hence difference equals 8′.

If, however, the hob flutes are cut to a spiral lead of 89·474 in. and the relieving is done by a gear ratio which corresponds to the 90·76 in., then there will be a slight variation in the height of hob tooth from one end of hob to the other. Assume hob to be 6 in. long, then the angular displacement of hob tooth to the flute would be

$$360° \left(\frac{6}{89{\cdot}474} - \frac{6}{90{\cdot}76}\right) = {\cdot}342°$$

For the 15 flute hob the angular displacement of the cam would be

$${\cdot}342° \times 15 = 5{\cdot}13°$$

Assuming the cam throw to be ¼ in. then the height of the hob tooth would be reduced by the following amount

$$\text{Reduction in height} = \frac{\cdot 250 \text{ in.} \times 5\cdot 13}{360} = \cdot 004 \text{ in.}$$

$$= \cdot 008 \text{ in. on diameter.}$$

In cases where neither slight-out-of-squareness of the flute nor reduction in the height of tooth over the length of hob is permissible the p.c.d. of the hob must be modified to suit the lead of 90·76 in. or whatever value is required by the work.

$$\text{Pitch diameter} = \sqrt{\frac{L \times P}{9\cdot 87}} = \sqrt{\frac{90\cdot 76 \times 2\cdot 625}{9\cdot 87}}$$

$$\therefore \text{p.c.d.} = \mathbf{4\cdot 913 \text{ in.}}$$

In other words, the 4·878 in. p.c.d. would have to be increased to 4·913 in.

The remaining point to receive attention is the dividing for the number of starts in the hob.

Dividing Multi-Start Spiral Flute Hobs

Where the number of starts divides evenly into the number of flutes it is only necessary to divide for the starts. The relieving drive must not be disengaged to do this, but cam spring pressure may be reduced temporarily.

For other cases, the change gear on the back shaft must be disconnected and division made for one start as in the case of a multi-start thread. Now the back shaft change gear must be turned forward through the following number of teeth.

$$\text{Revs. of back shaft} = \frac{N(L + P)}{S \times L} \text{Cos}^2\theta \quad \text{where} \quad \begin{array}{l} S = N^\circ \text{ of starts} \\ \theta = \text{Lead angle of thread.} \end{array}$$

Take the fractional part of the result, multiply it by the number of teeth on back shaft gear (*S* in Table of Gears) and the nearest whole number to this gives the number of teeth to be passed in turning the back shaft before replacing the back shaft gear. Alternatively, the setting for the second start after the first start has been relieved can be done by dividing for the number of starts and re-setting the timing cam visually, the setting being done by disengaging the relieving drive via the pull knob. It is important to note when relieving spiral work that the leadscrew must not be disengaged. The whole mechanism of the lathe must be reversed at the headstock, otherwise the timing of the relieving stroke will be out of phase with the teeth.

The relieving motion to the top slide operates in whatever direction the slide is swivelled, so that not only parallel cutters but also taper forms and end cutters can be relieved.

When the relieving mechanism is not required it can be isolated by withdrawing the gear seen located to the right of gear *N*. By pulling out

this gear the drive to the relieving unit is disengaged and the machine can be used as an orthodox machine tool for turning, surfacing and screw-cutting.

It will be noted that the maximum spindle speed for one flute is given in the table as 72 R.P.M., and the spindle speeds should be chosen so that the relieving tool does not make more than 72 jumps per minute otherwise the tool may not have time to withdraw and clear the work between each cut.

The swivel slide must be set to give a relieving motion perpendicular to the lathe axis when relieving the cylindrical surface of hobs and cutters. The auxiliary toolholder H must then be used to give side adjustment to the tool.

Exercises on Chapter VI

1. Find the change wheels required for the following threads : (*a*) 3 threads per inch ; (*b*) 10 threads per inch ; (*c*) 4½ threads per inch on a lathe having a leadscrew of 4 threads per inch.

2. Find suitable gearing : (*a*) for cutting a 20 threads per inch screw on a lathe having a leadscrew with ½-in. lead ; (*b*) 4 threads per inch on lathe with a leadscrew having 2 threads per inch.

3. Find wheels necessary for cutting the following threads : (*a*) 4-start thread having 20 threads per inch on lathe with 4 threads per inch leadscrew ; (*b*) to cut a thread having 8 starts and 16 threads per inch on same lathe.

4. Find the gears for cutting the following threads on a lathe with a 6-mm. pitch leadscrew : (*a*) ¼-in. pitch ; (*b*) 8 threads per inch.

5. Find gears for cutting the following metric threads on a lathe with a lead-screw with 4 threads per inch : (*a*) 2½-mm. pitch ; (*b*) 6-mm. pitch.

6. Calculate the leading and trailing angles for a tool to cut a square thread, triple start, 1½-in. lead on a steel bar 2¼ in. diameter. Sketch the tool, and on it indicate the width and the angles found as above. The top of the tool is on the centre-line of the work.

7. Draw a diagram indicating the gears connecting the spindle and leadscrew of a lathe set to cut one of the threads mentioned in Question 2, 3, or 4.

8. Describe with the aid of sketches the mechanism for operating the apron of a centre lathe, indicating the feedshaft, its method of reversing the traverse, clasp nuts for the leadscrew, etc.

9. Sketch three types of lathe-bed constructions showing the slideways, and indicate a method of taking up wear on the sliding surfaces.

10. Describe the operation of an automatic screw machine showing by suitable sketches how the front and rear cross slides are brought into the work.

11. Sketch a typical cam layout for a B.S.A.-type single-spindle automatic lathe.

12. Explain what is meant by cycle time, and give the values of the time taken for idle operations, and name these.

13. Describe the turret indexing mechanism of a B.S.A. auto.

14. Establish an expression for the relief angle A obtained on a cutter D in. diameter, having N teeth, by a 4-lobed cam, with C throw when making n revolutions per minute.

15. Calculate the angle of normal relief obtained on a cutter $3\frac{1}{2}$ in. diameter having 16 teeth, and sides inclined at 10° to the vertical by a 4-lobed cam with $\frac{1}{8}$ in. throw if maximum number of relief cuts is 60 per minute. Find also speeds of work spindle and camshaft.

16. Establish a formula for the angle of normal relief on a cutter with inclined sides, data as in Question 15, but with the cross slide set over 3° to give side relief.

17. (*a*) Describe with the aid of sketches how a square can be turned on a 2-in. diameter bar, showing relative positions of work and cutter.

(*b*) If the cutting speed is to be 150 feet per minute, calculate the revolutions per minute for the work and cutter spindles.

CHAPTER VII

PLANING, SHAPING, SLOTTING, BORING, AND DRILLING MACHINES

OF the machines dealt with in this chapter, planing, shaping, and slotting machines are of the same working principle ; in fact, the slotting machine is virtually a vertical shaping machine, whilst the planer can be regarded as a large shaper. The slotting and the shaping machines (the slotter and shaper) having moving tools which traverse the stationary work, whilst in the planer the work moves along and passes a stationary tool. In all cases the cutting stroke is at a low speed (particularly when compared with other types of machine) and the return stroke at a quicker speed. In shapers and slotters this is accomplished by a *link and slotted lever mechanism* or *Whitworth quick-return mechanism*, which will be described later.

To say that the planer tool is stationary is not strictly correct, as it moves across the work to provide the feed. Similarly, the work on the shaping-machine table also moves an amount equal to the feed at each stroke of the ram.

The shaping, slotting, and planing machines are now confined mostly to dealing with work which cannot be done on standard machines such as lathes and milling machines, the planing machine particularly being suitable for handling work the size of which is far too great for the machines already mentioned.

Some details of shaping and planing operations have already been given in Chapter I, and the points considered there should be borne in mind when reading through this chapter.

Also, in Chapter II mention was made of tests made in connection with varying rake angles and the corresponding variation in power consumption and tangential tool forces.

It is interesting to conduct similar tests for the shaping machine, and should the equipment be to hand data can be obtained as in the case of the lathe for turning tools. Even where the machine is not wired up to take a watt-meter, the test could be carried out with tools having different angles of rake and the surface finish and type of chip produced by each tool could be examined and compared.

Slotting Machine

Fig. 207 shows a general view of a Butler Slotting Machine, the Butler 30-in.-Stroke High-production Slotter.

This model, and the 21-in. and 36-in. ones, are equipped with separate

motors for the ram drive and power traverse, the motions of which are controlled by push buttons and an automatic contactor panel.

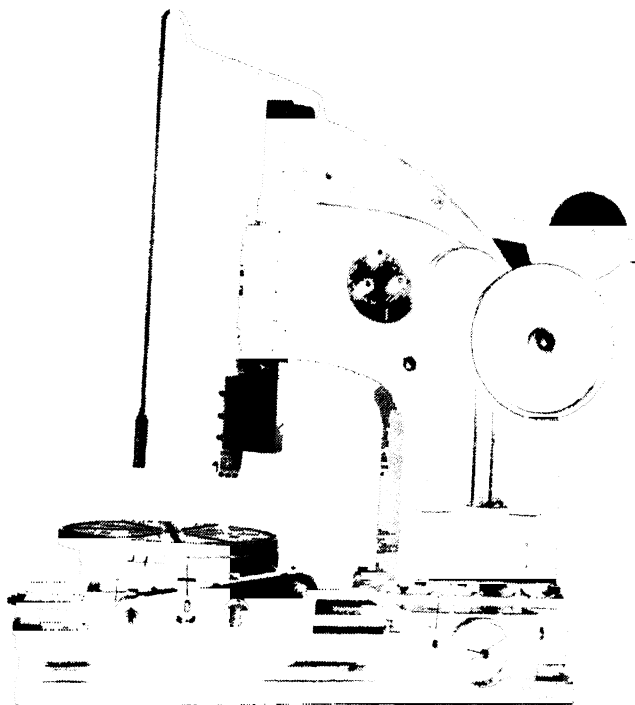
The power is transmitted through a six-speed gearbox, and the gears of this unit are of heat-treated nickel-chrome steel, with sliding members mounted on six splined shafts to the twin driving wheels. These twin

Courtesy Butler Machine Tool Co Ltd.

FIG. 207—BUTLER SLOTTING MACHINE

driving wheels are mounted in large-diameter bearings in each side of the body, and twin eccentric discs are fitted in each wheel, which are securely locked solid with the wheels by three bolts, one of which passes through both wheels and carries the phosphor-bronze driving block.

To alter the stroke, the three bolts are released and the wheels revolved by the flywheel, causing the discs to slip, thus varying the eccentricity of the driving bolt and consequently the length of stroke.

A cast-steel link and connecting rod transmit the power to the ram, and the whole is so designed that the connecting rod is pulling down

throughout the cutting stroke, ensuring an extremely smooth and powerful cut.

The twin driving wheels are shown in Fig. 208.

The Ram

This has large-section square guides, and on the 14-in. and 21-in. machines a forged-steel tool block is incorporated which ensures freedom from broken tee slots. On the larger 30-in. and 36-in. machines the ram face has a number of cast slots to accommodate the larger toolholders which may be used. The position of the ram with relation to the stroke may be adjusted by releasing the large nut and serrated plate on the ram

Courtesy Butler Machine Tool Co. Ltd.

FIG. 208—TWIN DRIVING WHEELS

front, and then moving the ram up or down from the square hole in the ram front.

The motion of the ram is controlled by a Whitworth Quick Return Mechanism, and a line diagram of this mechanism is shown in Fig. 209, from which the operation of the ram will readily be understood. It will be seen that a pinion meshes with and drives wheel D which rotates at constant speed on the eccentric boss C. Wheel D and disc E rotate on different centres, and the drive from wheel D is transmitted to E by means of a block H, which works in the slide in disc E. The slide can be seen in the illustration of the twin driving wheels (Fig. 208). The pin or bolt A moving in a circular path provides the stroke of the machine, the centre of the bolt circle being on the centre line of the machine.

The bolt F also moves in a circular path, but its centre of rotation is

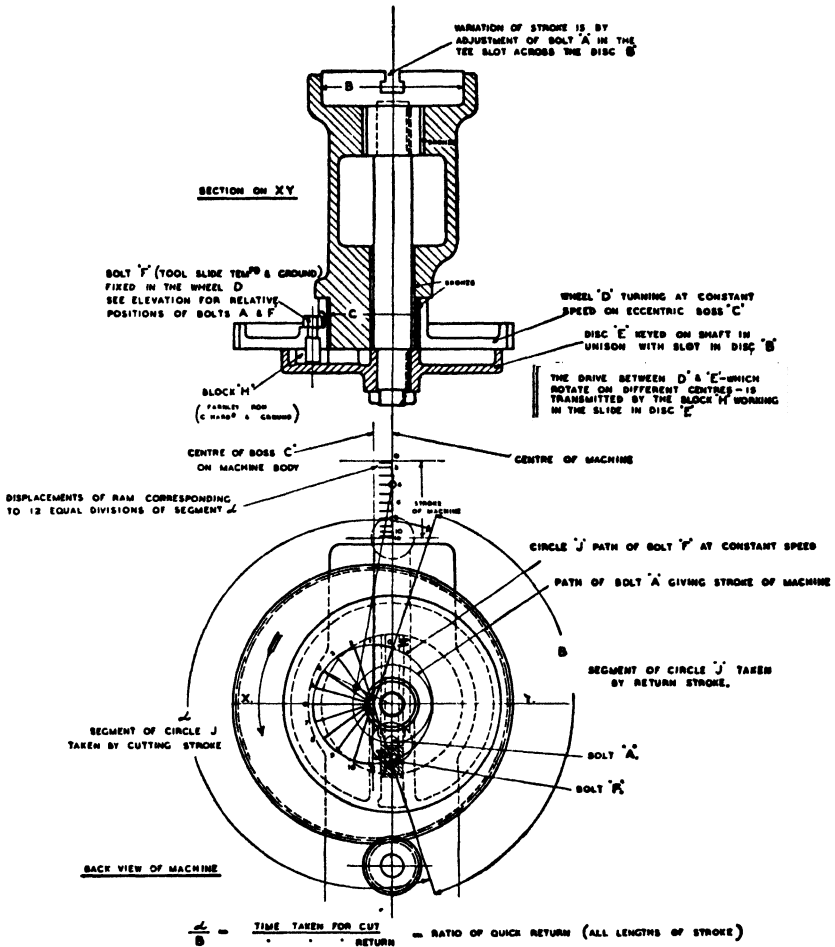
offset from that of bolt A, and this circular path is shown at J. The *intersection of these two paths at points x provides the quick-return* motion, since the cutting stroke occurs during the time that bolt *F*

Courtesy Butler Machine Tool Co. Ltd.

FIG. 209—WHITWORTH QUICK RETURN MECHANISM

traverses the arc of angle a and the return stroke during the traverse of arc B.

The ratio of the cutting stroke to the return stroke is thus given by:

$$\frac{\text{Time taken for cutting stroke}}{\text{Time taken for return stroke}} = \frac{a}{B}$$

and this ratio is the same for all lengths of stroke.

The bolt A is located in a tee slot across disc B, and the position of the bolt in this slot determines the length of stroke To shorten the stroke A is moved nearer to the centre of disc B

Machine Table

This unit is usually of the circular type, but can be replaced by a square table if desired.

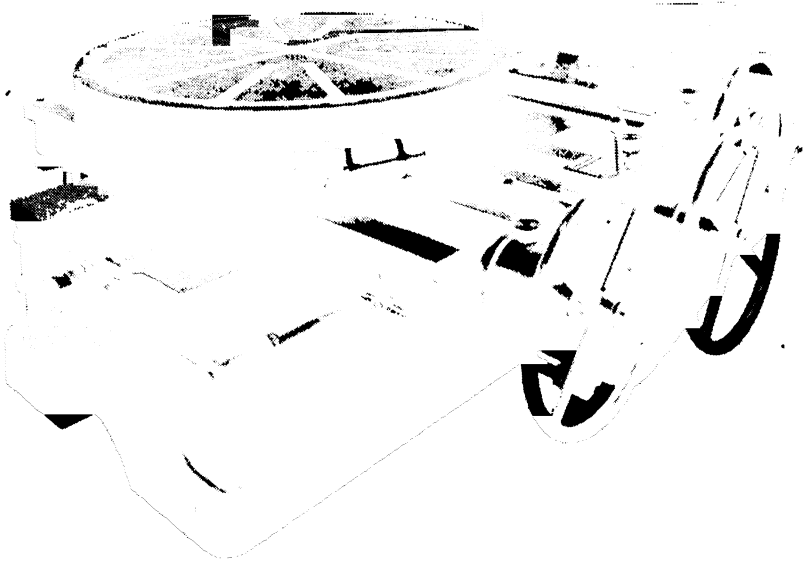
The table is provided with cast tee slots, the four rectangular cross

Courtesy Butler Machine Tool Co Ltd

FIG. 210—TABLE OF SLOTTING MACHINE

slots being machined by planing to give a square register, and the centre is bored true with the outside diameter. The solid full-depth outer ring of the table ensures extreme rigidity and strength against bolting strains.

Support for the table is provided by a substantial square slide and saddle, which have narrow guides and adjustable taper strips for taking up wear.

In addition, all feed motions to the table can be controlled by hand-wheels, and micrometer collars are fitted to facilitate the settings and feed rates. The periphery of the table is graduated in degrees. A view of the table is shown in Fig. 210.

Feed

The feed motion is taken from a fixed cam on the rear driving wheel to the feedbox at the front of the machine, and the amount of feed can be changed with the ram in motion or at rest. The amount of feed is indicated on a large dial which is concentric with the handwheel.

Power Traverse

The power traverse is driven by a belt or motor depending on the type or model of slotter, the drive being from the rear of the machine through the feedbox, and is controlled by the lever beside the handwheel. This

Courtesy Butler Machine Tool Co. Ltd.

FIG. 211—BUTLER 18-IN. SUPER SHAPER

lever selects the feed or power traverse, one being in the opposite direction to the other to avoid traversing the tool into the work. The toolholders are carried at the lower end of the ram, and a number of these are available, such as relieving toolholders which are fitted with an automatic spring relief, extension toolholders which enable larger diameters to be machined, and circular slotting toolholders.

Shaping Machine

There s a great similarity between the shaping machine and the otting machine, and many of the points affecting the machine design

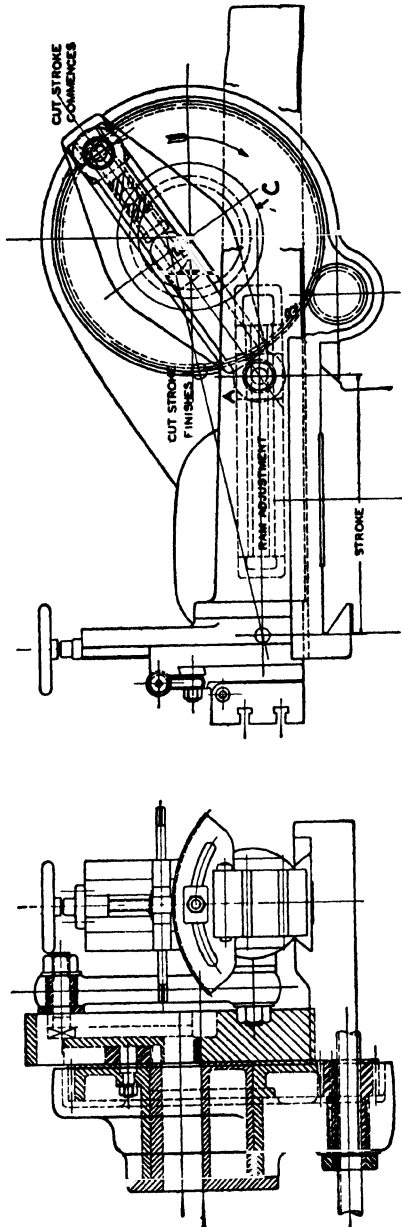



FIG. 212—WHITWORTH MOTION

Courtesy Butler Machine Tool Co Ltd.

are common to both types. The machine here described is a Butler Super Shaping Machine (Messrs. Butler Machine Tool Co., Ltd., Halifax, Yorks.).

This machine is made in two sizes, 18-in. stroke and 26-in. stroke, and a view of the 18-in. super shaper is given in Fig. 211.

The drive is by means of a friction clutch between the motor drive and an eight-speed gearbox, the gears, as in the case of the slotter, being of nickel-chrome steel, with sliding members mounted on a six-splined shaft. These gears are heat treated to give optimum conditions of service.

The stroke wheel is of the single helical construction, and revolves round a large-diameter fixed bearing in the body, with an extra bearing for the spindle.

The mechanism for driving the ram and providing it with the quick-return motion can be of either Whitworth quick-return motion or slotted link.

The first-named mechanism has already been dealt with, and there is no need to repeat the details. A view of a shaping machine using the Whitworth Quick Return Mechanism is shown in Fig. 212. This is a line diagram, and the motion in this design is placed above the ram of the machine.

The pinion *A* driving the gear *B* can readily be seen and the motion traced out. The crankpin on the gear-drive wheel moves in a circular path *C*, and actuates a block which slides in the slot in the lever and thus provides the motion for the ram, the offset *E*, between the centres of the crankpin and block, and the lever providing quick return.

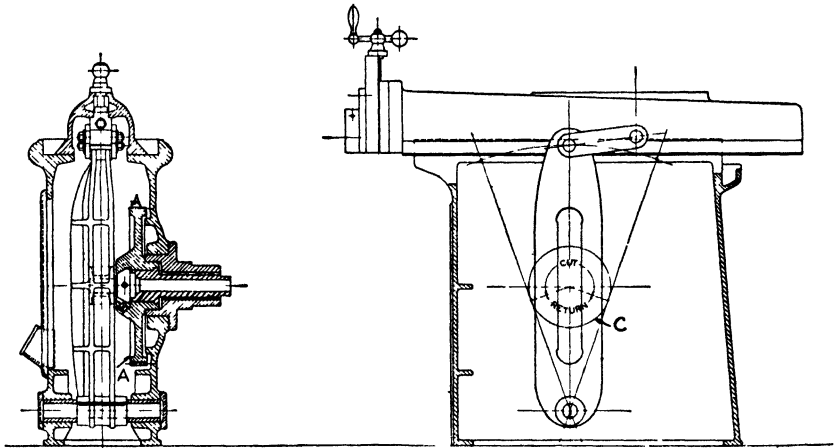
Another mechanism is the Link Motion of which a line diagram is shown in Fig. 213. The lever is pivoted at its lower end, being free to oscillate about a fixed fulcrum, whilst the upper end is fixed to the ram of the

Courtesy Butler Machine Tool Co. Ltd

FIG. 213—LINK MOTION

machine via a small connecting link. It will be seen that the gearwheel *A*, which is driven by a pinion mounted on the drive shaft, has a crankpin and slide-block as in the previous case. The crankpin circle shown at *C* provides the ram motion, and it will be seen that the two extreme positions of the ram, that is at the beginning and end of the stroke, are obtained, or rather fixed, by the two tangents drawn to the crankpin circle *C* from the pivot position at the bottom of the link. The two normals to these tangents when drawn from the points of contact to the centre of circle *C* divide this into the two segments which provide the quick-return mechanism of the ram. The ratio is shown on the drawing, and is similar to that already explained in the case of the slotting machines.

The Trunnion Mounted Link Motion

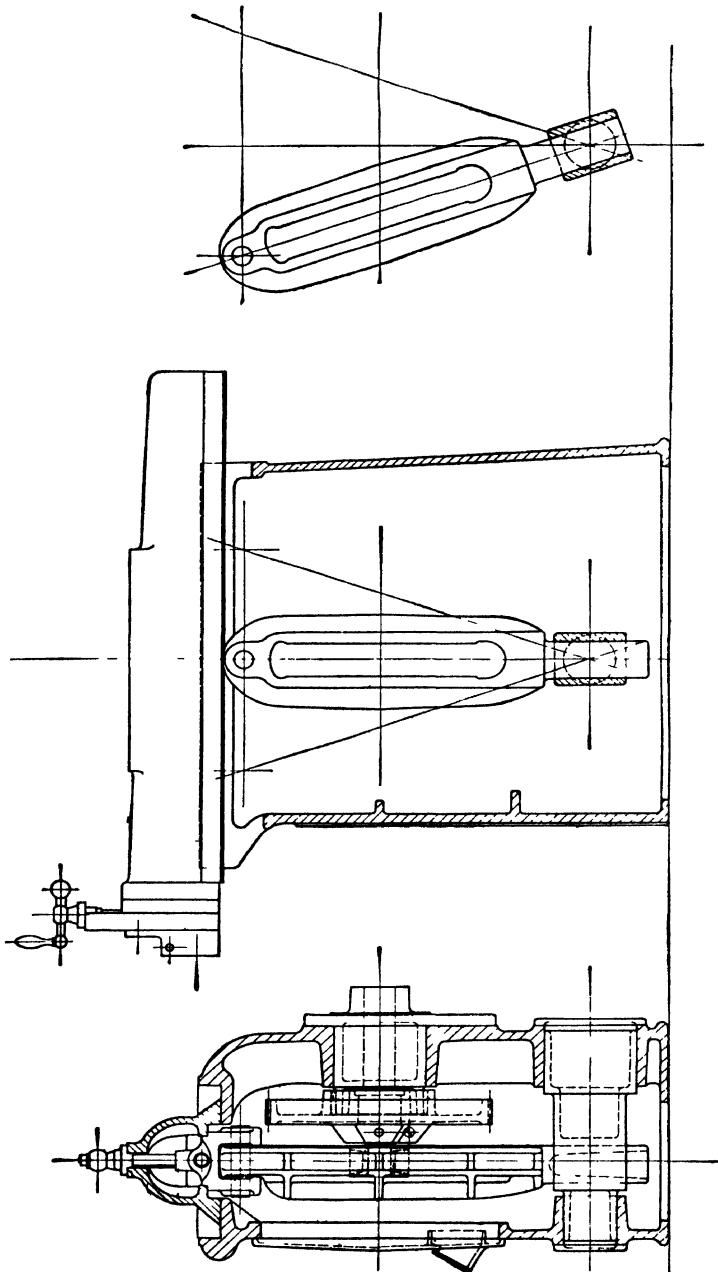
This is similar to the link motion just described, and is shown in Fig. 214. The main difference is that the top end of the slotted lever is fixed to the ram, and provision must therefore be made to accommodate the rise due to the arc of swing of the top of the lever, as indicated in Fig. 214. This is accomplished by the trunnion mounting.

Courtesy Butler Machine Tool Co Ltd

FIG. 214—TRUNNION LINK MOTION

The top end being fixed in the ram, and this in turn being constrained to move in a horizontal plane by its guides, the motion of the top end of the lever is also along a horizontal line. The lower end of the lever is free to slide in the trunnion which oscillates about its own centre, and thus the required motion is obtained.

The other important parts of the shaping machine are the table and toolholder. The table is moved by means of a table screw similar to the leadscrew of a lathe, that is, the longitudinal traverse of the table, and hence the work it carries is obtained by means of this screw. On the end of this screw is a toothed wheel, usually having 25 teeth. Thus, if the leadscrew has a thread of $\frac{1}{4}$-in. pitch, that is, 4 threads per inch, one revolution of the screw, and hence one turn of the toothed wheel, will move the work past the tool a distance of $\frac{1}{4}$ in.

The feed for such a case of 4 threads per inch screw and a 25-tooth wheel will therefore be $\frac{1}{100}$ in. per tooth.

$$\text{Feed per tooth} = \frac{\frac{1}{4}}{25} = \frac{1}{4 \times 25} = \tfrac{1}{100} = 0{\cdot}01 \text{ in.}$$

If two teeth are moved each time, then the feed rate will be:

$$\tfrac{2}{100} = 0{\cdot}02 \text{ in.}$$

In general, if n = T.P.I. of feed screw

N = No. of teeth in wheel

$$\text{Then feed per tooth} = \frac{1}{n \times N}$$

The feed wheel is turned round by a pawl which is driven by a small eccentric or crank drive from a small crankpin positioned in a tee slot cut across the face of a disc. As the pin is moved away from the centre of the disc the throw of the lever is increased, and therefore the throw or travel of the pawl is increased. This enables the pawl to travel over 2, 3, or 4 teeth, and thus increase the feed.

The table itself is a rectangular block with tee slots cut in it, and it can be raised or lowered and locked in any position to suit the work in hand. In the standard table just mentioned the tee slots are cut in three sides.

Other tables can be provided, and one of these is shown in Fig. 215. This is a combined swivelling and tilting table. In addition to the swivel arranged for, the table can be tilted to an angle of 15°. These two motions considerably increase the scope of the machine, and facilitate the machining of difficult or awkward shapes and angles such as compound angles.

Toolholders.—These, too, are worthy of mention, particularly the double toolholder box with curvilinear motion. An illustration of this is shown in Fig. 216.

Courtesy Butler Machine Tool Co Ltd

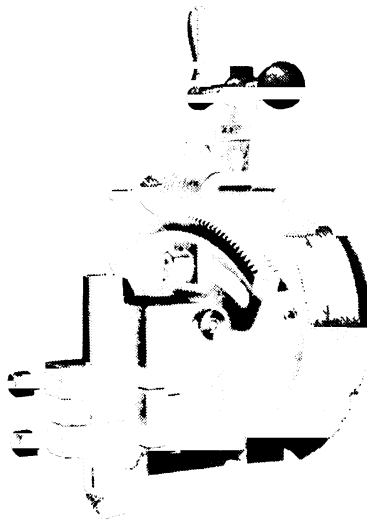
FIG 215—TILTING TABLE

Courtesy Butler Machine Tool Co Ltd

FIG. 216—CURVILINEAR TOOLHOLDER

Boring Machines

The subject of boring, and machines for this operation, is not always considered as completely as other phases of engineering production, yet the boring machine, or boring mill as it is termed, plays an important part in its own particular field of production. In construction, the boring mill is a robust machine capable of turning and boring parts which are large in diameter but comparatively shallow. To perform the same operations on any other machine, say a combination lathe, would necessitate a machine the size of which would occupy much more floor space than the boring mill, and herein lies one of the advantages of this machine. In making an initial comparison, the boring mill can be likened to a lathe standing on end, the table of the boring mill being horizontal and corresponding to the faceplate or chuck of the lathe which, of course, occupies a vertical position.

There are two main classes of boring machines, horizontal and vertical, the names referring to the position of the boring tool.

For the purposes of the work covered in this book we shall deal only with the vertical type of boring mill.

In all grades of engineering certain names stand out as recognised authorities in their own particular field, and in connection with boring mills, the name of Webster & Bennett Ltd., Coventry, is widely known. This company manufacture a range of boring mills the sizes of which vary from 36 in. to 60 in.

As has already been intimated, the table of the vertical boring mill rotates in a horizontal plane, and is mounted on a vertical spindle and supported by either flat or vee ways. The machine is compact, and the column is a monoblock, a one-piece case with a base to ensure rigidity. The general features of the machine can be appreciated by referring to Fig. 217, which shows a 60-in. Series " D " Vertical Turning and Boring Mill, and from this view the general construction of the machine can be followed. The table and the work it carries rotate in a horizontal plane, and there is no overhang as is the case with a lathe spindle, and consequently any error due to the spindle supporting the heavy workpiece is eliminated. The weight of the chuck and workpiece is carried by the track, and the dead weight, acting vertically downwards, keeps the work in a central position, and by virtue of the machine design the whole weight of the faceplate and work is carried via the track and bed casting through to the foundation. The spindle bearings are therefore only required to give lateral support to the vertical spindle and keep it in its central position, and this duty is performed by two parallel roller bearings at the upper end and a single-row ball journal bearing at the lower end of the spindle.

It is not generally appreciated that a boring mill can be arranged for multi-tooling, whereas in point of fact the machine, with its five-station

turret, can be multi-tooled to give a number of operations. Such a set-up is shown in Fig. 226, and it is worthy of note that the centres of the workpiece in the case of the component shown are held to a limit of 0·0002 in.

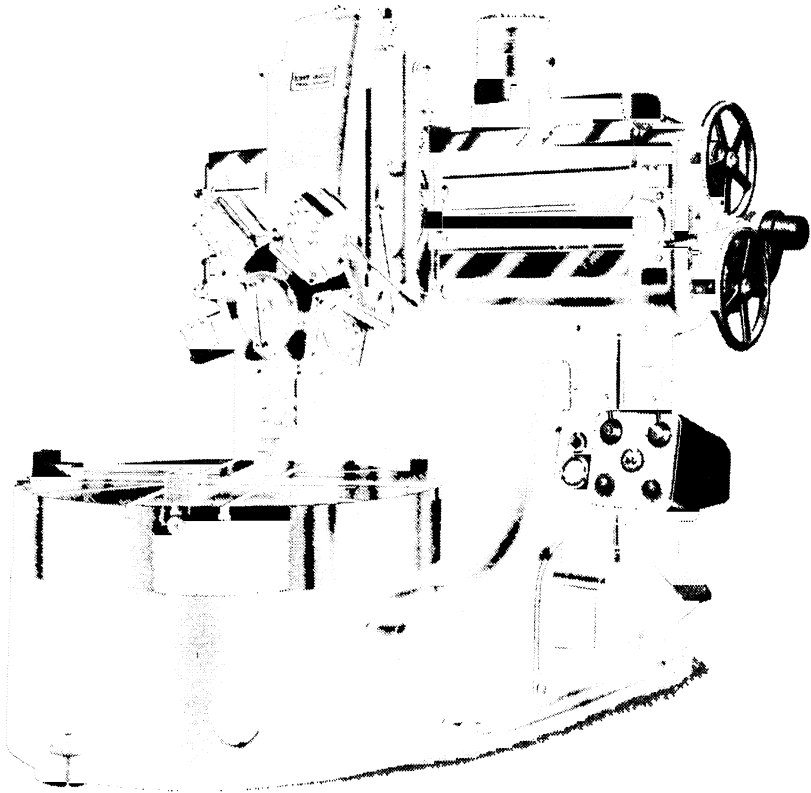
The normal position of the turret is with one of the five sides of the

Courtesy Webster & Bennett Ltd, Coventry

FIG. 217—60-IN. BORING MILL

pentagon horizontal, as shown in the illustrations; but for deep work this position requires an excessive tool overhang to enable the inclined face of the turret to clear the top of the work. To take care of this condition the turret is provided with an intermediate position, where it may be locked if necessary. A case involving the intermediate position is shown in Fig. 219, which indicates a pot being turned up by a special toolholder held in the intermediate position.

The turret can be adjusted to any position along the slide in which it is carried, and stops are provided on the vertical and horizontal rods which

can be used as dead stops for sizing work by hand or can be used as trips to control the tool travel.

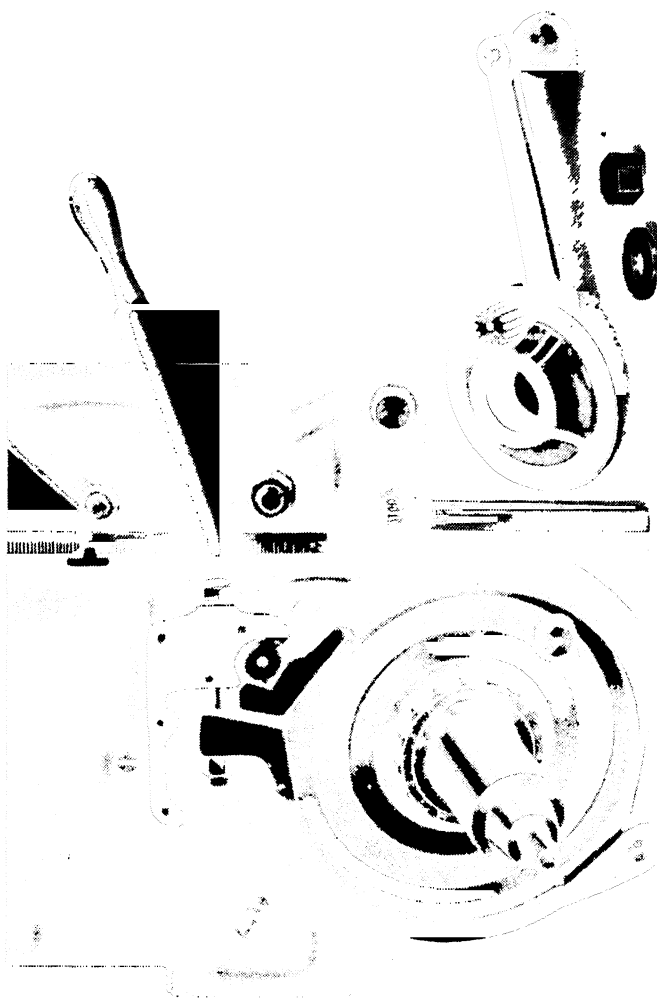
Permanent collars are fitted to the stop rods A and B (Fig. 220) to act as safety limit switches. The trip switches C can also be seen on the

Courtesy Wester & Bennett Ltd., Coventry.

FIG. 218—TURRET CLAMPING AND INDEXING MECHANISM

two rods A and B, and D is the solenoid operating trip of this Auto Electric Trip mechanism

There are many tooling arrangements available for use with the boring mill and of these the piston-ring equipment is shown in Fig. 221. The pot-type casting is machined in the bore and on the outside simultaneously,

and is rough machined and then finish machined at one setting, the operations in each case being completed at one pass.

The equipment as shown in Fig. 221 comprises a standard toolholder for facing the cast-iron pot, two gap-type toolholders, one for roughing and one for finishing, as shown in actual operation in the illustration, and one multiple parting toolholder which is adjustable to suit the width of the piston ring. Thus, after finishing the bore and outside diameter of the ring, four rings can be parted off. Alternatively, a facing and parting toolholder can be used, and each ring parted separately, one side being

Courtesy Webster & Bennett Ltd Coventry

FIG. 219—INTERMEDIATE POSITION OF TURRET

faced true. This is particularly useful when the rings are ground to width, as a perfectly flat surface is available for locating the ring on the grinding-machine table.

Another interesting layout is that used for axle-box equipment, and Fig. 222 shows an easy " set-up " used for machining railway axle boxes. This equipment consists of two self-centring jaws which grip the axle box on the horn cheeks. One of the jaws carries an auxiliary jaw with a micrometer adjustment to allow the horn cheeks to be offset to the centre of the axle-box bore, and accommodates an offset of $\frac{3}{16}$ in. in either direction. A pair of end stops is provided for locating and setting the position of the bore relative to the end of the box.

The standard types of tools for use with boring and turning mills are shown in Fig. 223, as are some of the standard toolholders. The increased use of tungsten-carbide tools is reflected in the tungsten tipped tools shown in this illustration, and as in other phases of metal removal, so in boring, the advantages of tipped tools are utilised in heavy cuts or high speeds.

Machine Construction

The boring mill, as already explained, is a rigid construction, the column being a one piece casting which is carefully machined, and the bore

Courtesy Webster & Bennett Ltd, Coventry

Fig. 220—Auto Electric Trip

for the spindle being the important point. All faces and machined parts are located from this bore, which is machined first in order to obtain the spindle location and generally check the casting. With this bore machined and central, the remaining parts can be machined in correct relationship to the bore.

The cross slide which carries the saddle is of sturdy design, ribbed and boxed at the rear to give maximum rigidity when secured to the main column.

Courtesy Webster & Bennett Ltd Coventry

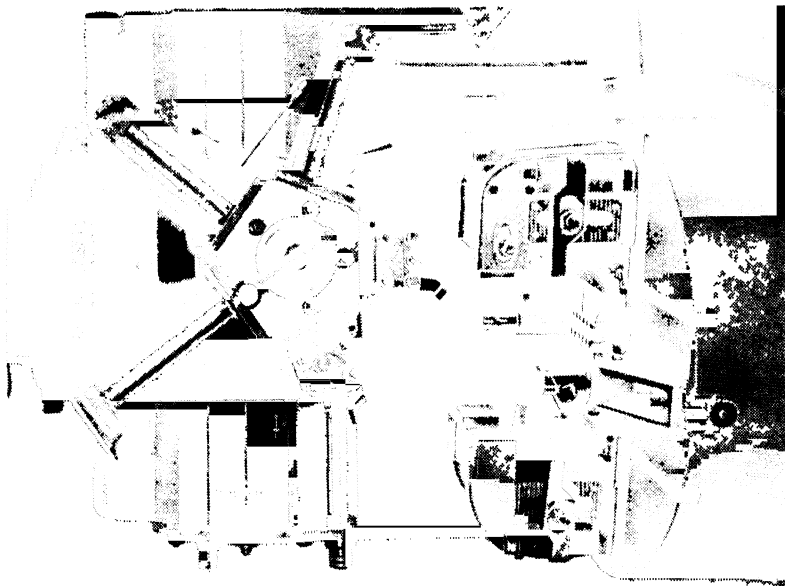
Fig 221—Boring Piston-ring Pot

Courtesy Webster & Bennett Ltd, Coventry

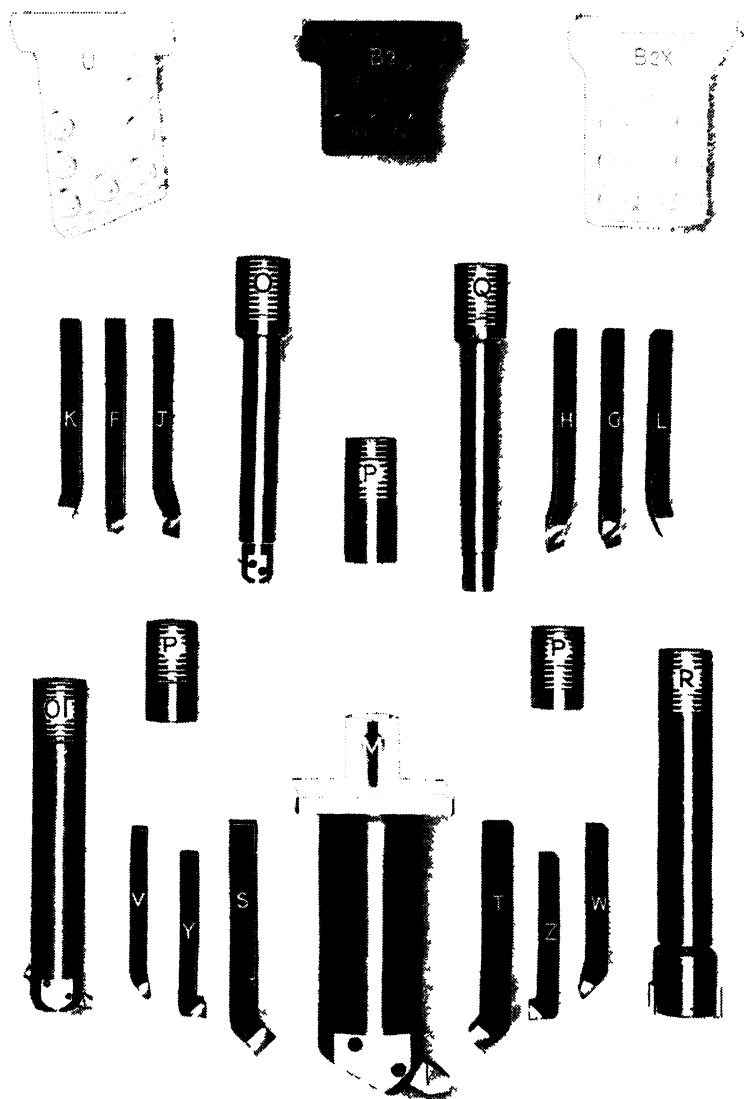
Fig 222—Set-up for Boring Axle Boxes

Courtesy Webster & Bennett Ltd., Coventry

FIG. 223—STANDARD BORING TOOLS

The saddle and swivel which are the guiding bases for the turret are carried on the cross slide. A rear view of the saddle is shown in Fig. 224, from which the slides for mating with those on the cross slide can be seen and also the bevel wheel and pinion for the turret swivelling.

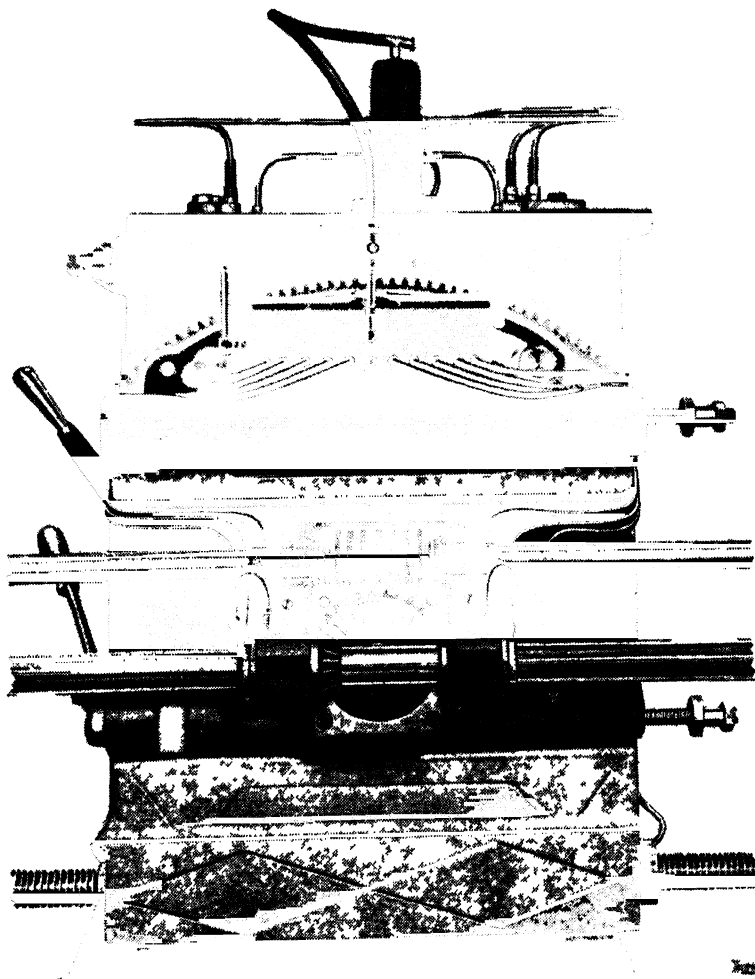
Turret.—The turret itself is an important part of the boring mill, and obviously the accuracy of the finished work is directly dependent on its freedom from chatter. This freedom is obtained by a robust construction

Courtesy Webster & Bennett Ltd., Coventry

Fig. 224—Rear View of Saddle

incorporated in the super turret mechanism which is indicated in Figs. 224, 225, and 226.

The pentagonal turret is made from a steel forging. The faces are machined and bored in position, and then provided with tapped holes

for the attachment of toolholders and special tools and attachments. The turret holes are gauge size, and are fitted with quick-acting positive grips for holding boring bars. The turret is revolved by gearing, and indexing by hand is facilitated by this arrangement.

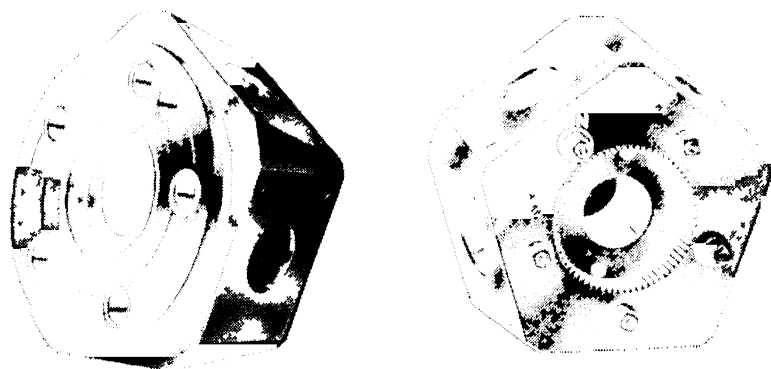
To lock the turret in position, a powerful and efficient locking arrangement is provided, and this will retain its accuracy indefinitely. It binds the turret solid with the slide over its entire base. Referring to the

Courtesy Webster & Bennett Ltd., Coventry

FIG 225—TURRET

diagrams of the turret (Figs. 224, 225, and 226), the following list will simplify the study of its operation

J. Forged-steel turret.
K. Flange which is gripped by the binding ring.
L. Hardened and ground locating bushes.
M. Jig drilled and tapped holes for securing toolholders.
N. Rack pad fastening for securing small boring bars, collets.
O. Internal gear for revolving turret.

Speed Box.—This unit provides 12 speeds arranged in geometrical progression (see Chapter II), and the latest design incorporates hydraulic operation. The sliding gears are interlocked with the driving clutch and hydraulically operated internal expanding brake. The speed box and control bridge is shown in Fig. 227, and from this the general construction can be seen. The gears are of nickel-chrome steel with ground teeth, and slide on splined shafts which run in ball and roller bearings. The control bridge controls the positions of the gears and the clutch interlock.

Chuck and Spindle Arrangement

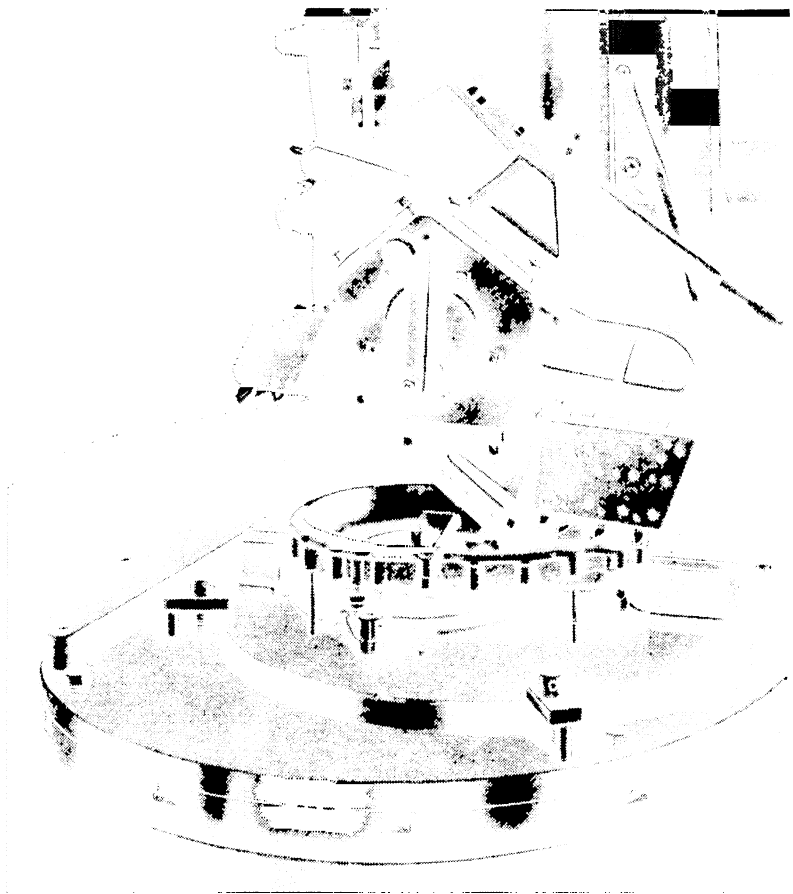
These are made either of the vee-ring type or flat-ring type. As explained earlier, the design of these parts facilitates the accurate

Courtesy Webster & Bennett Ltd, Coventry

FIG. 226—MULTI-TOOLING SET-UP

production of components on these machines Referring to Fig 228, *A* is a forged-steel hollow spindle which is spigoted, bolted, and dowelled to the chuck *D* The two parallel roller bearings *B* hold the spindle in alignment *C* is the high tensile steel single helical internal gear, which is also spigoted, bolted, and dowelled to the chuck. *D* is the chuck which is of a robust ribbed construction, the ribs being visible in the illustration. *E* is the large-diameter vee-ring bearing which rests on the chuck seating.

Chuck Drive and Seating.—This is seen in Fig. 229. *A* is a hardened

and ground pinion, with single helical teeth, which drives the internal gear *C* (Fig. 228). *B* is the chuck seating which supports the vee ring *E*. *C* is the rim of the base which is enveloped by the chuck rim. It is grooved and drained by draining holes to prevent the ingress of cutting coolant, dust, or other foreign matter.

The design of the chuck, spindle, and track depends on the type and

Courtesy Webster & Bennett Ltd Coventry

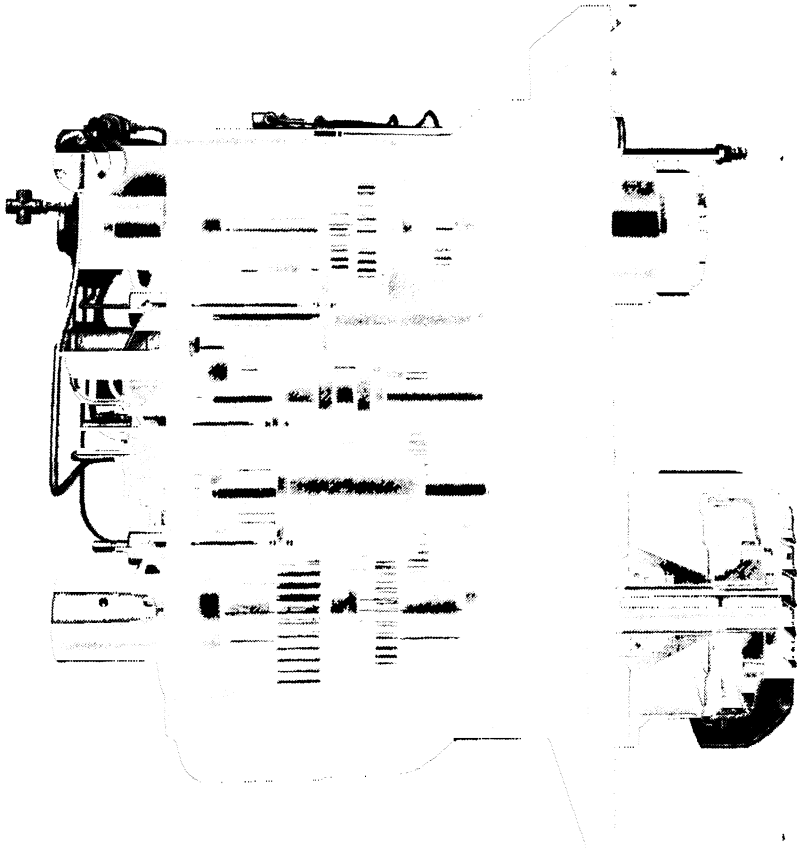



FIG 227—SPEED BOX

duty of the machine. For the normal or low-speed types the vee track is used. For the high-speed type a flat track.

The faceplate and spindle arrangement for the flat track is shown in Fig. 230. The general design follows that for the vee type just described, but has the following differences: the drive is by a single helical external gear *C* made from high-tensile steel and spigoted, bolted, and dowelled to the faceplate *D*. The large-diameter flat track *E* supports the work

Courtesy Webster & Bennett Ltd Coventry

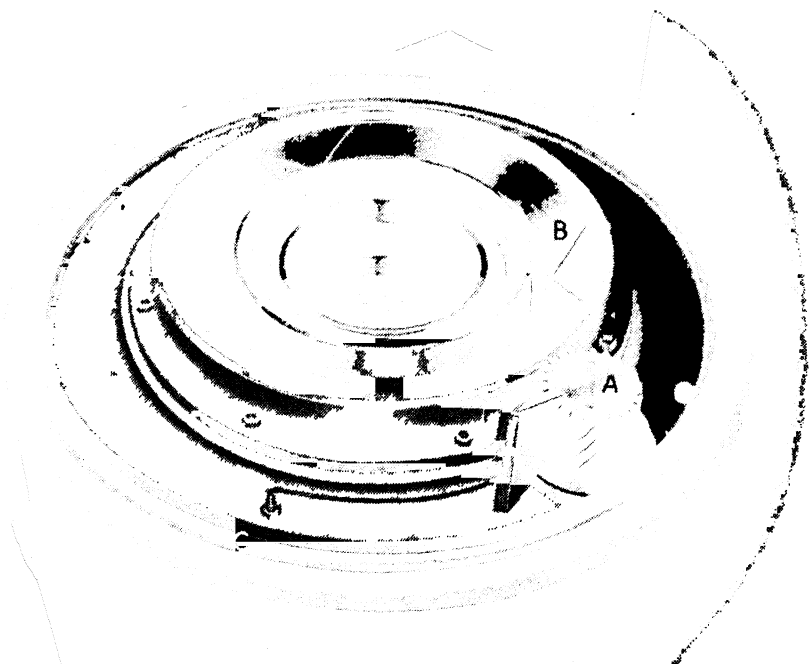
FIG 228—CHUCK AND SPINDLE ARRANGEMENT

Courtesy Webster & Bennett Ltd., Coventry

FIG. 229—CHUCK DRIVE AND SEATING

and faceplate in the manner already described. For high speeds the vee track is not as suitable as the flat track, owing to the action of the increased centrifugal force at the higher speeds tending to cause the chuck to ride on the track and not on the bearings, with a resulting increase in friction. In the flat track the force, not being resisted by the horizontal flat track, is carried directly by the roller bearings which are selected with these points in mind.

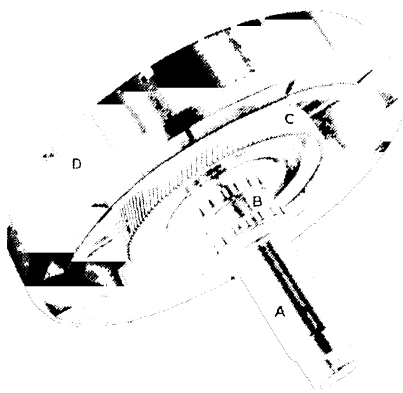
These machines are capable of removing considerable stock of hard steel at the lower speeds or cutting light alloys at high speeds. At one time the Duplex type of boring mill having two tables was used. Work

Courtesy Webster & Bennett Ltd., Coventry

FIG. 230—FACE PLATE AND SPINDLE ARRANGEMENT

could be set up on one table and the operation started up, and then the operator could set up the second table and start a job on this one and return to the first, arranging the work so that the components would be finished alternately. Nowadays, however, the increase of cutting speeds resulting from the use of the tungsten-carbide tipped tools makes this method impracticable, and the Duplex type of machine is rarely made.

The latest type of machine is of hydraulic operation, presenting a neat appearance and eliminating the speed- and feed-change handles, etc.

A section through the table and chuck of a boring mill—showing the vertical spindle and flat track—is shown in Fig. 230A. This view and those in the earlier pages of this chapter should make clear the general features of the boring machine.

Drilling Machines

Drilling is perhaps the commonest of all the operations performed in engineering. Very few are the parts which do not call for drilling, if only to remove some of the surplus metal and facilitate the final shaping of

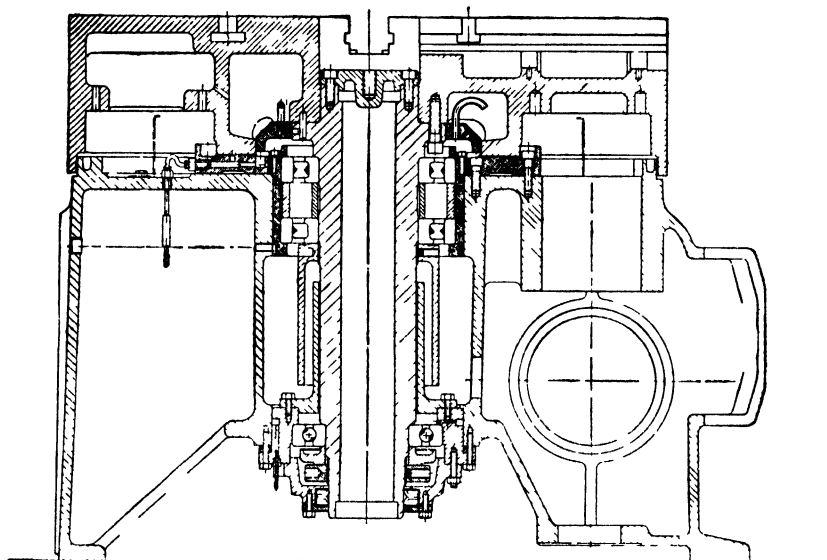
the work. The earliest of exercises with which a student is familiar sometimes require that parts of the work be removed either by hack sawing or chipping and filing, and very often a few suitably sized holes are drilled first to facilitate the later work. Thus the student is introduced early to the use of drills and the drilling machine, particularly the Sensitive Drilling Machine. The sensitive drill is, as its name implies, one which is fed by hand, so that the operator can " sense " or " feel " the progress of the drill through the work, particularly at the point where

Courtesy Webster & Bennett Ltd., Coventry

FIG. 230A—SECTION THROUGH BORING MILL CHUCK

the drill breaks through the material. In this way the amount of feed can be varied to suit the prevailing conditions.

The range of machines in this class is most extensive, and varies from the small hand drill and portable pneumatic and electric drills to bench drills, sensitive drills, pillar drills, general purpose drills, radial drills, multi-spindle drills, unit heads, and horizontal drills. In addition, there are the special drills which are used for drilling long beams and girders used in building and bridge construction. These girders are far too big to handle in the ordinary machines, and, moreover, could not be handled in an ordinary shop. Therefore the drilling machine is designed to run along the beams and girders and drill the holes for rivets and bolts in the required positions. No matter what the type or design of the machine, the quality of holes depends on the drill, and the drill is very important.

With a correctly ground and sharpened drill and a machine which is designed and built so that it holds the drill rigidly, the drilling of holes is straightforward. The greatest cause of drill breakage is possibly due to using them in machines which are not rigid enough for their work.

Drills.—The twist drill (see Fig. 231) is generally formed by milling two equal and diametrically opposite helical grooves in a cylindrical piece

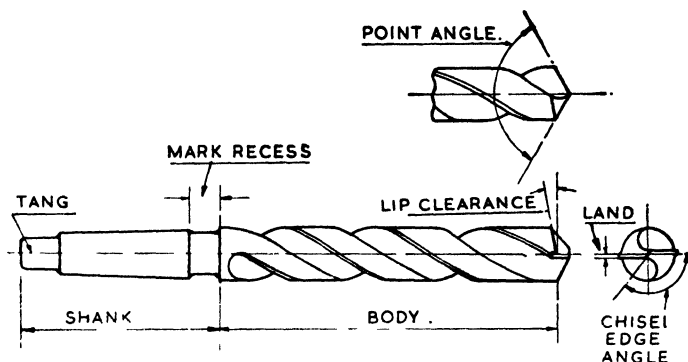



FIG. 231—DRILL TERMS

of tool steel. These grooves, called " flutes," have four specific purposes :

1. They help provide the proper cutting edges on the cone-shaped point.
2. At their junction with the cutting edges they are shaped to curl the chip tightly within itself, so that it occupies the minimum space.
3. They form channels through which the chips and swarf have free passage within the hole as it is drilled.
4. They also act as channels taking lubricant to the drill cutting point.

The main parts of the drill are the shank, body, and point.

TABLE 12

Material	*Peripheral Speed, ft./min.*	
	Minimum	*Maximum*
Mild steel	30	120
Tool steel	40	100
Nickel alloys	45	60
M.S. drop forgings	50	60
Cast iron	45	145
Malleable iron	85	145
Bronze	70	300
Magnesium	240	410
Aluminium	200	300
Monel	70	145
Bakelite	100	150

Body.—The part extending from the shank to the outer corners of the cutting lips.

Shank.—The part by which the drill is held and driven. There are various forms of shank, the most usual being the taper shank, which is precision ground to ensure perfect drive. A good fit between the taper shank and socket is, in most instances, quite sufficient to give positive drive without the aid of the tang.

Further details regarding drills are given in the second volume, "Jig and Tool Design," in which will be found details of design—material, drill faults, etc. The recommended speeds for H.S.S. Twist Drills are given in Table 12. These should be contrasted with those given in Table 3.

The above values, quoted by Wm. Asquith & Co., Ltd., are based on a survey of drilling practice in various parts of the world. The variation between the minimum and maximum values is due to the wide variation of materials covered by each classification.

Feeds.

TABLE 13

Drill Diameter in in.	*Feed, in./rev.*
Under $\frac{1}{8}$.	0·001–0·002
$\frac{1}{8}$–$\frac{1}{4}$ . .	0·002–0·004
$\frac{1}{4}$–$\frac{1}{2}$ . .	0·004–0·007
$\frac{1}{2}$–1 . .	0·007–0·015
1 and above	0·015–0·025

Whilst drills are dealt with in the second volume, as already indicated, it will be of interest to mention the main terms applied to drills and give a typical sketch of the parts referred to. The rake and clearance angles of ordinary lathe tools have been considered in Chapter II, and for drills the angles are as follows: the clearance angle, or lip clearance, is the relief which is given to the cutting edges in order to allow them to enter the metal without interference. In Fig. 232 sketch A shows a drill which would not cut, since the surface *C* would always be in contact with the metal and prevent the cutting lip from biting, to enable the lips to penetrate and cut. The surface *C* must be ground away at the back of the lips (see Fig. 232, sketch B). The surface *C* is now shown lower than at *A*, the difference between these two lines being the measure of the clearance. The correct way to grind the surface at the back of the cutting lip is shown in Fig. 232, sketch C. The lip relief for general-purpose work, average conditions, is 12–15° as shown, and this is the angle at the circumference of the drill and should be increased towards the drill centre. The line across the centre of the drill between the cutting edges, i.e. the dead centre,

should have an angle of not less than 125° or more than 135°, as shown in sketch D, Fig. 233.

When the drill point has been correctly ground (and here it should be noted that if the relief angle is too large the edges break away due to lack of support and the drill will not penetrate if it is below the 12–15°), the drill should be checked to ensure that the lips are of the same length and that the angles of both lips are equal and correct, this angle being 59° for ordinary purposes (see Fig. 233 (E)).

The rake angle is shown in Fig. 233 (F), and since this is established at the time of making by the drill manufacturer, it should not be altered.

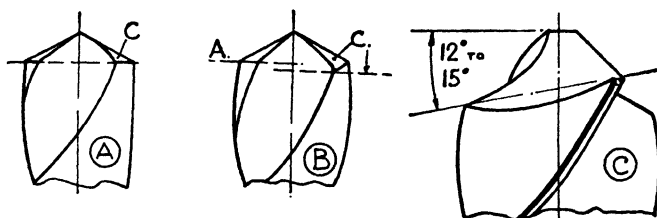



Fig. 232—Drill Angles

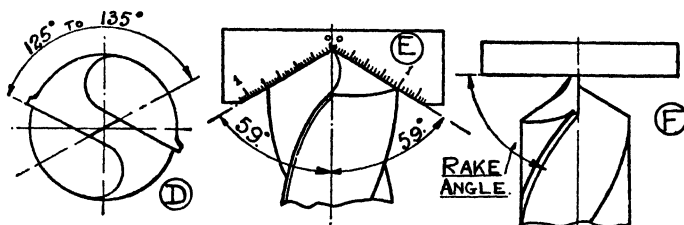



Fig. 233—Drill Angles

Some detail of the drilling machine has already been given, and it now remains to consider the main types of this machine. Perhaps the most common is the vertical type, and an example of this is shown in Fig. 234. This machine has a capacity up to 3 in. when drilling continuously in cast iron or steel, and occasionally up to 3½ in.

The drilling head is made as a unit, and the spindle is driven by a solid portion provided with six splines, and is carried in a sleeve in which it revolves in a bronze bearing. The rack for the feed motion is cut from the solid in the steel sleeve, which is amply supported in the drill head even when fed out to the maximum distance. The feed motion can be either a fine-hand feed or variable-power feed. Quick hand adjustment of the spindle is provided by the handwheel, which can be seen on the front of the saddle, and further slight movement of the handwheel after the drill point has made contact with the work engages the power feed.

Fig. [illegible]4—Vertical Type Dr[illegible]ng Machine

Fig 236—U G D Vertical Drilling Machine with Circular Table

Courtesy Wm Asquith Ltd

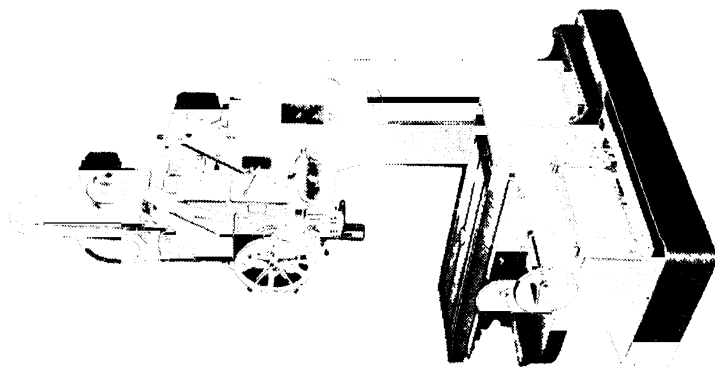



Fig 235—U G D Vertical Drilling Machine

Reverse motion of the handwheel disengages the power feed and withdraws the spindle.

The machine shown in Fig. 235 is a U.G.D. vertical drilling, tapping, boring and studding machine, and is a versatile type with a wide range of general utility. It can be adapted to receive various types of work-table and multiple drilling heads. The general details are similar to those just described, and the capacity of the machine is drilling from solid in cast iron or medium carbon steel up to 2½ in., light boring up to 7½ in. diameter, tapping 2 in. Whitworth in mild steel, tapping 2½ in. diameter, i.e. 2½ in. Whitworth in cast iron.

A variation of this type of machine is the U.G.D. vertical spindle Duplex drilling machine, which consists of two standard heads mounted at fixed centres, one head being arranged for left-hand control. Each spindle is fitted with a two-spindle head and a special fixture for guiding the tools.

The circular, rotating table is provided with three stations, one for loading and unloading, one for drilling, and one for reaming the component, which, in the illustration shown, was for an aero connecting rod. The machine just referred to is shown in Fig. 236, from which the details can be followed.

Horizontal Machines

In addition to the more usual vertical type, there are the machines designed for horizontal drilling. Such a type is shown in Fig. 237, which is an R.G.2 horizontal drilling, boring, tapping and studding machine. The machine consists essentially of a substantial traverse bed.

The column is fitted to this traverse bed, along which it has easy adjustment on rollers, being controlled from a handwheel on the spindle slide; a single lever on the slide securely locks the column on the bed simultaneously with the locking of the slide on the column. The operator's platform can be seen at the foot of the column.

The spindle slide is of compact form, and is adjustable on the column by means of a handwheel located on the same centre as that for traversing the column along the bed, and an efficient balancing system is incorporated in the design.

Spindle.—The spindle is of special steel, heat treated to 60–70 tons in the driving part and to 120 tons at the morse taper end. Varying rates of self-acting feed are available. Power feed to the spindle is of a patented self-engaging type, which is applied by bringing the twist drill into contact with the work by means of the quick traverse handwheel and exerting a little additional pressure at the moment of contact. The details of the spindle-feed motion are similar to those already described for other machines.

Its capacity is such that it can drill continuously holes up to 2½ in. diameter in iron and steel.

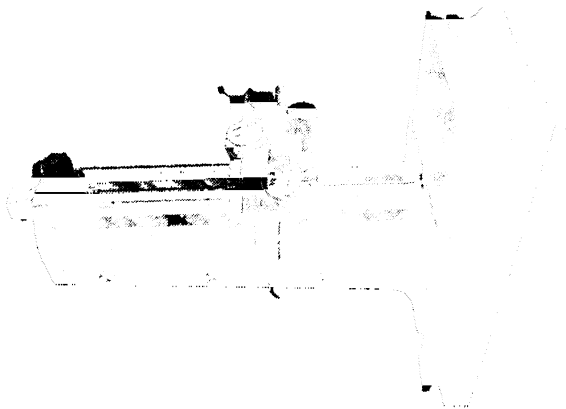



Fig 237—R G 2 Horizontal Drilling Machine

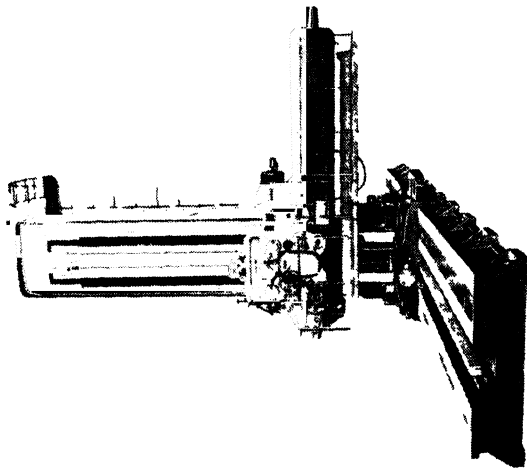



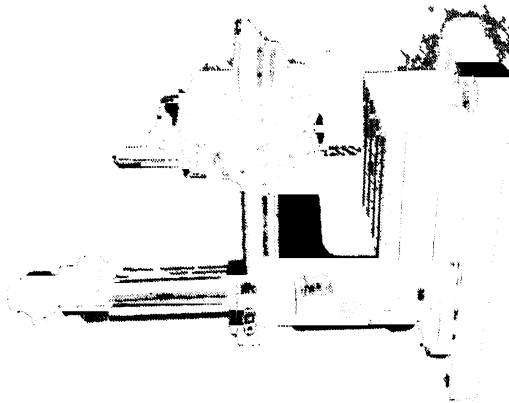
Fig 238—H F B Horizontal Drilling and Milling Machine

Courtesy Wm Asquith Ltd

Fig 239—O D 1 Radial Drill

Another type of horizontal machine is the H.F.B. machine which is illustrated in Fig. 238, showing a horizontal drilling, boring, facing and milling machine. In general design it is somewhat similar to the previous machine, in that it has a traverse bed on which the main column can be moved by means of a rack and pinion, the rack being visible in the centre of the traverse bed.

The column is a massive, well-proportioned casting ribbed internally for conditions of maximum strength and provided with guide ways of liberal dimensions for receiving the spindle slide.

The spindle is of special high-tensile steel accurately ground, and has variable hand and self-acting feed motion in both directions. The control of the stop, start, and spindle reverse are electrical.

Surfacing Slide.—This has self-acting radial feed to the surfacing slide via a nut and screw from a differential motion driven from the faceplate through a separate gearbox.

To give an idea of the size of these machines, the spindle diameter is 6 in., the faceplate diameter 3 ft. 1½ in., the length of the traverse bed 16 ft. 6 in., and the approximate weight of the machine without electrical equipment is 40 tons.

Radial Drills

This type of drill is a well-known and useful machine tool, and Fig. 239 shows the Asquith O.D.1, the 6-ft. O.D.-type machine which is a radial drilling, boring, tapping and studding machine. The machine consists essentially of a vertical column or pillar, which is designed and constructed to give maximum rigidity and to ensure resistance to deflection at all working heights of the arm. On the 3 ft. 6 in.–6 ft. sizes the pillar is of two diameter form, but on the 7 ft.–9 ft. sizes the pillar is of one diameter throughout, which allows for a low minimum height between the spindle and the baseplate, at the same time allowing a maximum height under the spindle.

The Arm.—This member also is of robust design for negotiating the heavy demands of modern production. It is well ribbed and braced to ensure maximum resistance against lifting and twisting stresses.

Spindle Slide.—This is carried on the arm in such a way as to provide free and rapid adjustment. The slide occupies an extremely well-balanced position on the arm, along the ways of which it traverses on ball-bearing mounted rollers of good diameter and width. Thus, rigidity and accuracy of spindle alignment are assured, and the slide is capable of being securely locked on the arm in any desired position. The drive to the spindle is from a motor mounted on the spindle slide through highly efficient gearing. The motor is brought as near to the spindle as is practicable, and frictional losses between motor and the cutting tool are reduced to a minimum.

Speed Changing.—For this operation a lever moving in a " gate "

path in conjunction with a second (double-gear) lever placed just below enables twelve changes of speed to be obtained. A direct-reading index plate clearly shows the lever positions for the desired speeds.

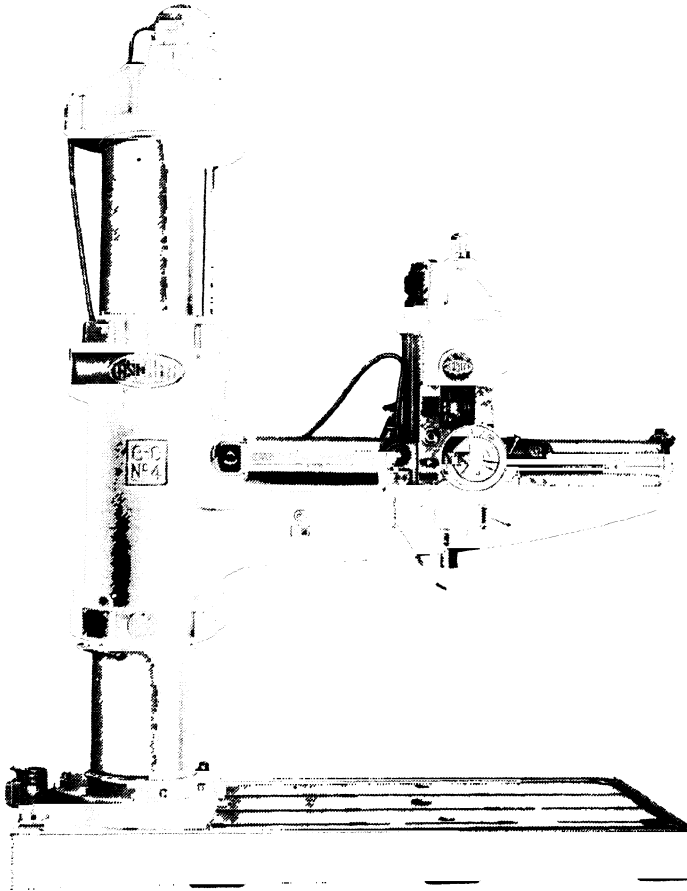
Feed Changing.—There are four rates of spindle feed available, selected by a direct indicating lever adjacent to the spindle. Any of the

Courtesy Wm Asquith Ltd

FIG. 240—O D 4—RADIAL DRILL

feeds can be used with any of the spindle speeds. There is also provided a patent combined lock for locking the spindle on the slide, an automatic trip motion for use in drilling holes, i e. repetition holes of equal depth, and a patent ejector device enabling drills and sockets, etc., when not cottered, to be instantly ejected by merely winding the spindle back sharply to its top position

A larger type of radial drill is the O.D.4, illustrated in Fig. 240, from which it will be seen that the pillar is of the one-diameter type as distinct from the two-diameter pillar of the O.D.1 machine shown in Fig. 239.

The general features of this machine are similar to those which have just been described and also as contained in the descriptions of the other drilling machines, but the following variations are incorporated in the design. A range of nine feeds is available for use with each spindle speed.

A push-button feed lock which, by pressing on a button, brings the self-acting feed motion into operation whilst simultaneously locking the spindle slide on the arm and the arm on the pillar. Further pressure disengages the feed and unlocks the machine.

There is also a patented speed selector for the easy selection of peripheral cutting speed for the size of hole being drilled. This is built into the front of the spindle slide and makes use of a new principle depending entirely on the diameter of hole being drilled.

In connection with other work, it has been stated elsewhere in this book that students will already be familiar with some aspects of the work in hand, and this also applies in the case of drilling machines. The student will be familiar with the hand drill, bench drill, and sensitive drill, and the aim here is to extend that knowledge and provide additional information and also to describe the latest trend in developments and design.

The latest type of drilling machine is the Tru Speed type. There are two models of this machine at present available, the Nos. 2 and 3, and these are shown in Figs. 241 and 242. The development concerns the spindle slide, and a closer view of this unit is shown in Fig. 243. This new unit, the Tru Speed Spindle, embodies the following features. There is an infinitely variable spindle speed throughout the whole available range; the exact speed for any desired diameter of cutter within the capacity of the machine and to suit any specific material can be readily applied. Moreover, the speed of the drill or cutter can be varied, if desired, during the actual cutting operation. The speed range is split up into six groups, any of which can be brought into operation immediately by the operation of a gear-change lever. This new type of control enables effortless changes to be made without the clashing of gears, and the main driving motor is automatically cut out during changing and restarted when the change is completed. The spindle feed of this machine is of new design, and the engagement of the final power feed is by pivoted levers mounted on a rack shaft, these controls being used also for quick hand traverse of the spindle when power feed is disengaged by the action of a separate lever. The arrangement is such that it permits highly efficient sensitive feeding.

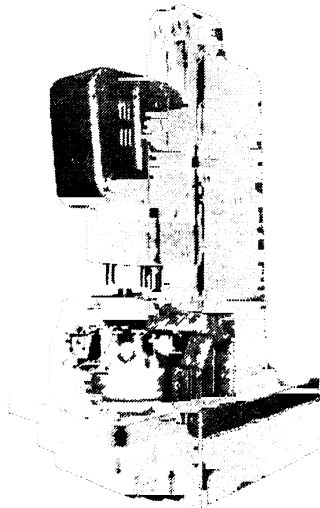
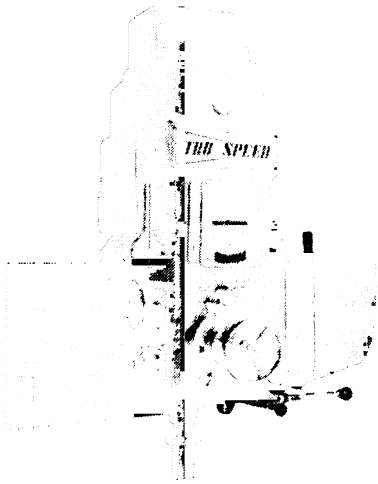
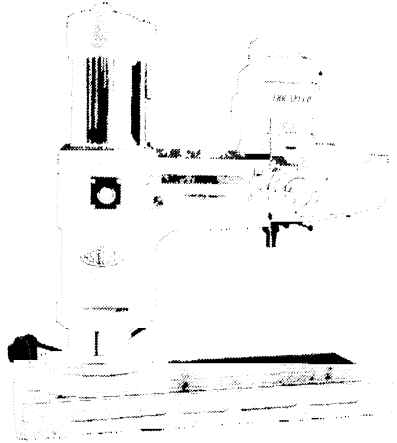
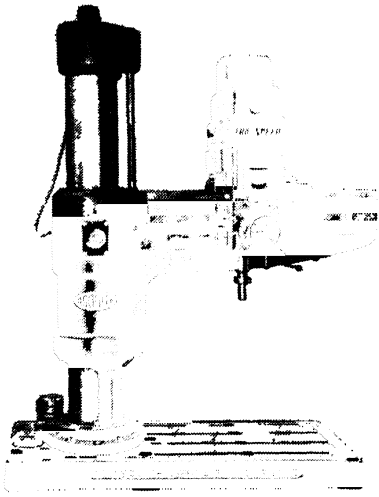
There is an entirely new form of speed selector and indicator which enables the appropriate speed for the diameter of the hole and the material being drilled to be selected instantly and applied, and the indicator registers the exact speed at which the spindle is running. The recommended

Courtesy Wm Asquith Ltd

FIG. 241—Top Left TRU SPEED HEAD RADIAL DRILL FIG. 242—Top Right TRU SPEED UNIT FIG. 243—Bottom Left TRU SPEED UNIT FIG 244—Bottom Right VERTICAL UNIT HEAD

cutting speeds for a variety of materials are indicated at the top of this device.

All the previous features of the machines are available in modern design, and there is also a built-in light for illumination of the cutting point incorporated in the spindle slide. The No. 2 machine covers 3 ft. 6 in.,

4 ft. 6 in. and 6 ft. radius, and is made in these three sizes. The No. 3 machine is made in sizes to cover from 6 ft. to 12 ft. radius.

A close-up view of the Tru Speed unit is shown in Fig. 243, from which the various points just mentioned can be followed.

Unit Head Machine

Another development in design, and one likely to be adopted in many fields of production engineering, is the unit type of head. This can be applied to any of the types of machine previously dealt with, i.e. either horizontal or vertical, as is the case with the Tru Speed unit which is applied to the ordinary-type pillar drill. These machines using the unit head are high-production machines constructed entirely on the unit principle, which enables a machine to be built up in various multiway forms to meet any particular requirements. In this manner different multi-spindle heads and attachments can be readily interchanged without interfering with the basic construction of the machine. The unit head is designed for right- or left-hand mounting in the horizontal, vertical or angular plane.

There is a Cam Unit type, in which the unit head is of sturdy box section arranged to receive multi-spindle heads or other attachments. The bolt and pin holes for these auxiliaries are jig drilled to ensure interchangeability, and a standard slot is provided across the end of the main spindle for driving the attachments. The spindle is driven from a flange-mounted motor on the head through spur gears which can be changed in order to vary the spindle speed. The feed drive is taken from the spindle through spiral gears, change gears, and a final worm and wormwheel to the drum-type cam. The feed cycle can be varied by changing the feed change gears and cam, thus making the unit adaptable over a wide range of operations. The slideways of the machine are arranged as standard to give a 4-in cam stroke and 9-in. hand feed.

The operation is simple, easy, and effective, and the standard cycle of operations is:

1. Engage the push button for the spindle and cam rotation, causing the head to travel quickly to the feed position.

2. The cam lead changes from quick traverse and the head feeds in to the required depth at the feed rate.

3. Continued rotation of the cam quickly returns the head to its original position, where a trip dog on the cam strikes a limit switch and stops the motion.

In other machines the above cycle is modified:

3. The limit switch on the unit strikes an adjustable trip dog and reverses the driving motor.

4. The reverse rotation of the cam following (3) withdraws the head to the starting-point, where a trip dog on the cam strikes a limit switch in the head and all motion ceases.

Other types include a cycle of operations with quick power traverse When the push button for the cycle start is pressed, the head moves to the point of commencement of the cam cycle, and the limit switch or the head strikes an adjustable trip dog, causing the traverse motor to stop under " plugging conditions " and the spindle motor to start revolving. The unit head now goes through the cam cycle as indicated and then the trip dog on the cam strikes the limit switch inside the head stopping the spindle motor and starting up the quick traverse motor in the reverse direction. This causes the head to return to the loading station at the quick rate, where a limit switch on the head strikes a fixed trip dog on the bed and all motion ceases.

Vertical Unit Head Machine.—A typical example of this is shown in Fig. 244. In this illustration the various points of the construction can be followed, and on the table can be seen the fixtures for holding the work during the drilling operations, the neat lines, grouped electrical controls and general appearance of this machine being self-evident.

Horizontal Unit Head Machine is a similar machine, except that the head is in a horizontal position ; the general features will be seen by reference to Fig. 245. The slot across the main driving spindle to the right of the push-button control panel, and, as already explained, a multi-spindle head can be attached to the unit head, the multi-spindle attachment being designed for the particular work in hand. Whilst no attachment is shown in the case of the horizontal machine, a multi-head is shown on the vertical machine in Fig. 244.

One adaptation of this machine is for cylinder boring, in which case the head is fitted with a six-spindle attachment. This is shown in Fig. 246. The six spindles can be seen, although only four are shown in use—evidently for machining the bores of a four-cylinder I.C.E. block. Also in this illustration the jig for holding the work can be seen bolted to the bed of the machine.

In Fig. 245 the machine is shown without any attachments, and it can therefore be adapted to any special use, and as can be seen, the machine is provided with a special form of fixture-base on which can be located the jig or fixture for the work.

Multi-spindle Machines

It will be evident, from the details just given of the machines available, that these can be used for high-production work, and such is the case.

These unit heads can be fitted with multi-spindle attachments, and drill up to 34 holes in a component at one operation. It should not be taken that the number of holes just cited is a maximum—it is given as an actual case in which 34 holes are drilled simultaneously in one operation taking under 1 minute to perform. The holes are positioned to fine limits, as they have to assemble with other components machined on other units.

An example of this multi-spindle drilling is shown in Figs. 247 and 248. In these illustrations the drills are mounted in the attachments on the unit heads, and the work-holding fixture mounted between the two heads. The component can also be seen in front of the machine, and

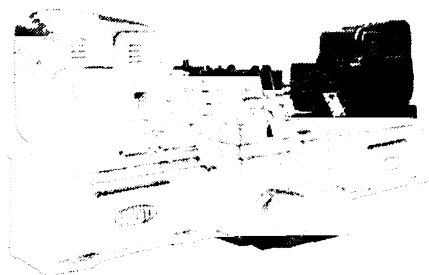
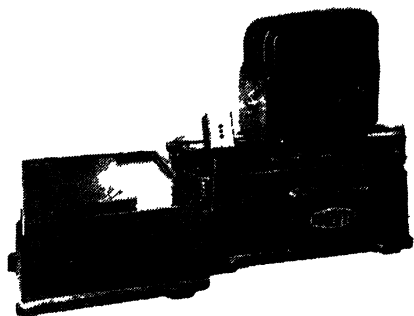
FIG 246—CYLINDER BORING MACHINE

Courtesy W'm Asquith Ltd

FIG. 245—Top HORIZONTAL UNIT HEAD

FIG 247—Bottom HORIZONTAL UNIT HEAD MULTI-SPINDLE DRILL

FIG. 248—Right UNIT HEAD MULTI-SPINDLE DRILL

17 holes which have been drilled in the two cover flanges, 11 in the larger flange and 6 in the smaller. A similar operation is required for tapping the holes with the necessary thread for the studs with which the covers are held in position on the finished component. The details of the work-holding jigs and fixtures, the guiding bushes, etc., for the drills are dealt with in the volume on " Jigs and Tools "

Courtesy Wm Asquith Ltd

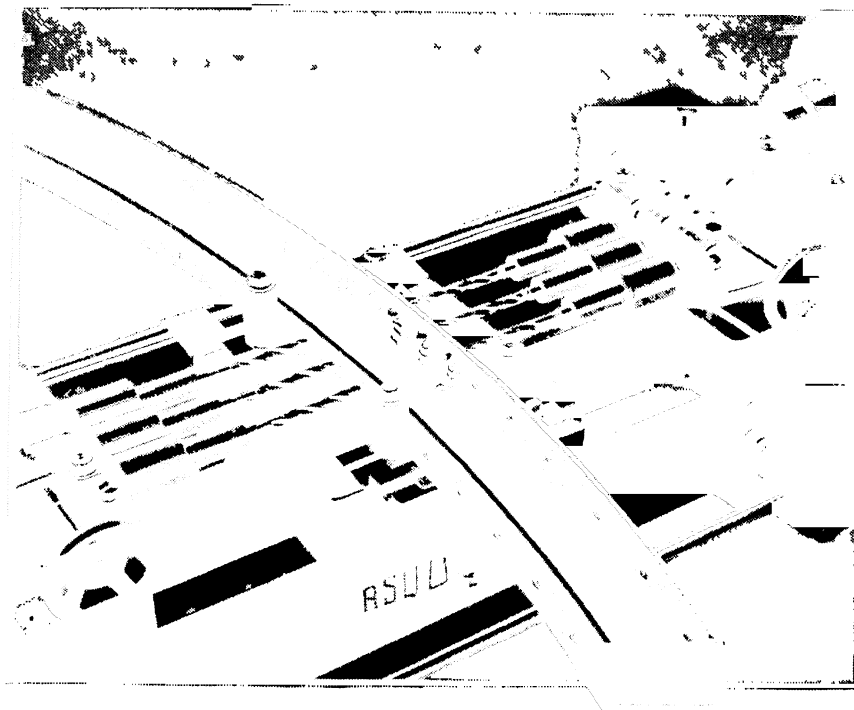
FIG 249—DUPLEX THREE-SPINDLE HORIZONTAL DRILL

Courtesy Wm Asquith Ltd

FIG 250—GIRDER DRILLING

An example of a horizontal drilling machine, a Duplex three-spindle drilling machine, is seen in Fig. 249. It is used for drilling channels and girders, etc., the operation being considerably simplified by this machine with adjustable spindles and rollers to facilitate handling the work (Fig. 250).

Exercises on Chapter VII

1. Describe one of the following machines: (*a*) slotting machine; (*b*) shaping machine.

2. How is the quick return of the cutting tool obtained in a slotting or shaping machine? Sketch the mechanism used for this purpose.

3. Express the theory underlying the Whitworth Quick-return Motion.

4. (*a*) If the angle moved through during cutting stroke is 220° and during return stroke 140°, what is the ratio of cutting time to return time per stroke of ram?
(*b*) If the crankpin of the above motion makes 75 r.p.m., calculate the actual time for cutting stroke and return stroke respectively.

5. Describe how the feed motion is obtained in a shaping machine and say how the feed is reversed. If the table screw on a shaping machine has 5 threads per inch and the ratchet wheel on the end of screw has 50 teeth, what is the feed per tooth?

6. Describe the main features of a boring mill.

7. List the main parts of a standard twist drill and make a sketch showing what you have listed.

8. On the above sketch or on a suitably prepared diagram indicate the clearance angle, rake angle, point angle, etc.

9. Give a list of suitable (*a*) cutting speed, (*b*) feed, and (*c*) spindle revolutions per minute for drilling ¼-in., ½-in., and 1-in diameter holes in mild steel.

10. Describe a drilling machine, mentioning its main features, and include a description of any modern type of machine with which you are familiar or have read about.

CHAPTER VIII

GEAR CUTTING

GEARS can be produced by two methods:

1. By using a formed cutter and dividing head on a Universal milling machine.
2. Generated by special cutters on a gear generating machine.

Before dealing with the machines, it will be advisable first to consider the work produced by the gear cutters and the terms used in connection with gears.

Firstly, we come to the form of the gear tooth, which is now standardised on the involute, not many cycloidal-shape teeth being made apart from replacements for old machinery.

The involute curve can best be illustrated by the unwinding of a cord from a cylinder, and if such a cord, having a loop at one end, carries a pencil, the pencil will describe an involute curve when the cord is unwound from the drum, the cord, of course, being kept taut. This is shown in Fig. 251, which also shows two such involutes, unwound from the same circle and forming the flanks of a tooth.

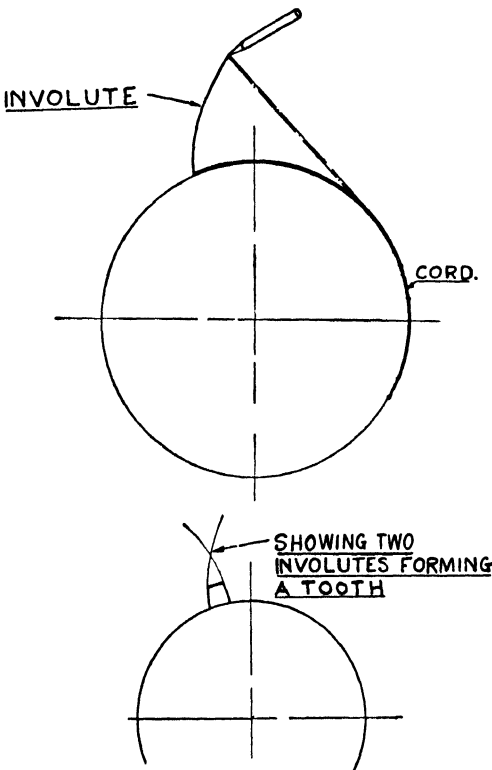



FIG. 251—METHOD OF DRAWING INVOLUTE CURVE

The involute curve obviously will vary with the variation in the diameter of the circle, known as the base circle, from which it is generated. As the diameter increases, the involute flattens out, until in the limit the

curve of the involute becomes a straight line generated from a base circle of infinite radius. This leads us to the straight-sided rack, which is used for generating involute teeth on gear blanks in the " Sunderland " gear-cutting machine and similar types. Before going on to consider the principle of these machines, we shall consider the terms used in connection with gears in general and the main points which underlie the operation of mating gears.

The involute form is used because of its many practical advantages,

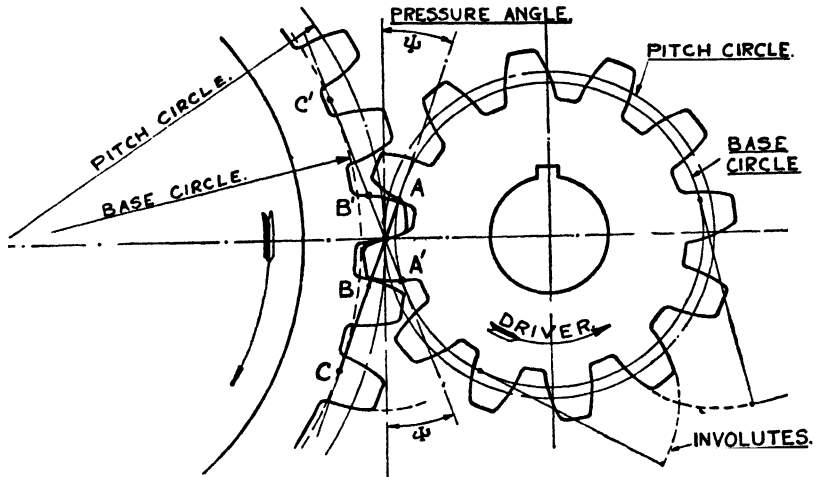



FIG. 252—LINE OF ACTION AND PRESSURE ANGLE

amongst which is the fact that the true involute rack has straight sides and is therefore easy to produce, and the wheel teeth produced by such a rack have comparatively simple curves. Further, a pair of mating gears of the involute type have the advantage that they may be run at a greater centre distance than that for which they were designed and still run with theoretical accuracy. The limiting condition is that they shall not be so far separated that one pair of teeth goes out of contact before the next pair come into mesh. This fact eliminates the necessity for absolute precision in locating shaft centres, together with the fact that they can be run at a closer centre distance if the teeth are cut deeper than the required depth at the designed centre distance.

The Line of Action

The action or contact of tooth curves is as shown in Fig. 252, from which it will be seen that this contact takes place along the lines connecting the base circles and representing an imaginary crossed belt. Contact begins at *A*, where the involute starts, and ends at *B*, both points being on the line *A*—*C*, the line of action. Had the driver been rotating in the oppo-

site direction, the line of action would have been on line A'—C', the contact in this instance beginning at A' and ending at B'. The pressure angle or angle of obliquity is the angle formed between the line of action and the common tangent. If other diameters of base circles were used, the line of action would have passed through the pitch point P at a different angle and the teeth would have had a different involute form. The pressure angle ψ is used to define the base circles and tooth form, such as $14\frac{1}{2}°$ tooth or 20° tooth when the pressure angle is $14\frac{1}{2}°$ or 20°.

To preserve the condition of constant angular velocity ratio, one pair of teeth must come into action or engagement before a pair disengages. The length of the path of contact is determined by the intersection of the

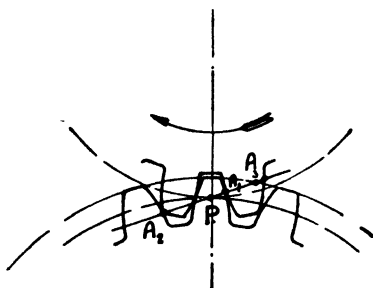



DIAGRAM SHOWING CONTACT RATIO.

CONTACT RATIO = $\frac{A_1 A_2}{A_1 A_3}$

FIG. 253

line of action with the addendum circles at points A_2 and A_3, and this must be equal to or greater than the base pitch $A_1 A_2$.

The contact ratio is given by

$$\frac{\text{Distance } A_1 A_2}{\text{Distance } A_1 A_3}$$

The points illustrating the above are shown in Fig. 253.

Method of Drawing the Involute Curve

To draw the curve shown in Fig. 251 using a pencil in the end of a cord is not a practical method, and for cases where the involute curve is required the following can be adopted :

Referring to Fig. 254, it will be seen that the base circle is divided into arcs of equal length 1, 2, 3, 4, etc., and the radial lines 01, 02, 03, etc., drawn. Now the tangents T_1, T_2, T_3–T_{10}, are drawn, and on these tangents are marked off the lengths of chords 2 : 1, 3 : 1, 4 : 1–10 : 1 on the respective tangents. Drawing through the points thus obtained, the involute curve results as shown, and this is further clarified in the smaller

diagram, which shows a small portion of an involute near to the base circle.

The method of drawing the involute curves now being established, the points mentioned in connection with the design of any pair of gears having involute teeth can be drawn out. The case depicted in Fig. 255 is for two gears, or could be treated as a gear blank and gear cutter. For the case where a rack is used, the conditions are as indicated in Fig. 258, which shows a rack and pinion condition or a " Sunderland " type of rack cutter generating a blank. In this instance it should be remembered that all gears which mesh correctly with the same rack have the same base

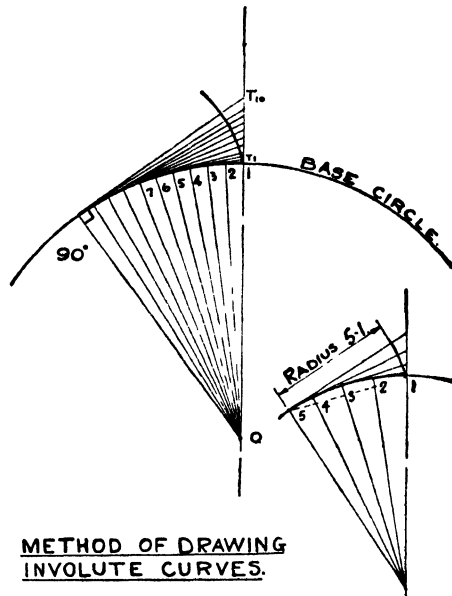



FIG. 254

pitch, which gives involute teeth the property, already referred to, of giving a constant angular velocity ratio even when the centre distance is changed. Referring again to Fig. 255, it will be seen that the common tangent to the two base circles, T_1T_2, is normal to both involutes, and contact therefore between the involutes must take place along this line as shown. The pitch point P is fixed by the diameters of the base circles and centres, and is independent of the point of contact of the involutes. Therefore, since the normal to the point of contact of the tooth profiles always passes through this point, the profiles will always transmit a constant angular velocity ratio given by :

$$\text{Velocity ratio, V.R.} = \frac{OP}{OQ}$$

So much for the preliminaries. The following list gives the main terms encountered in gear problems. When the word diameter is used, it is always understood to mean the pitch diameter, viz. *d* or *D*, Fig. 255.

Circular pitch is the distance, measured along the pitch circle, from the centre of one tooth to the centre of the next tooth = C.P.

Diametral pitch is the number of teeth to each inch of its pitch diameter. If a 20-tooth wheel has a pitch diameter of 2 in., then there are 10 teeth to each inch of pitch diameter and the diameter pitch is 10, that

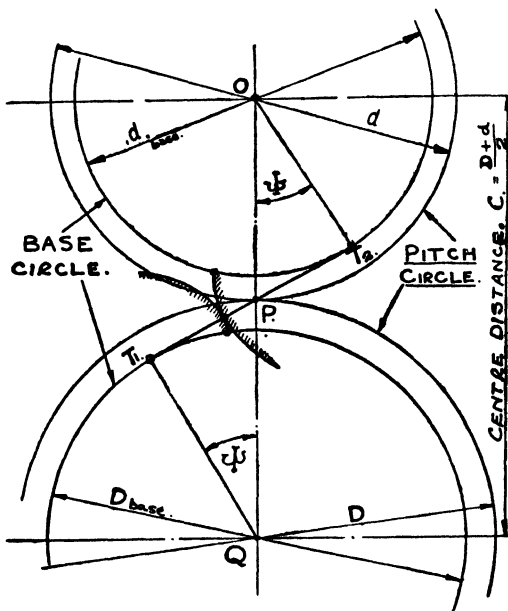



FIG. 255—GEAR TOOTH INVOLUTES

is to say, the gear is 10 diametral pitch, usually written 10 D.P. Therefore, with the number of teeth in a gear given and the diametral pitch also, divide the number of teeth by D.P. to obtain the pitch diameter. To obtain the circular pitch from the diametral pitch, divide 3·1416 by the diametral pitch.

$$\text{D.P.} = \frac{3\cdot1416}{\text{Circular pitch}} = \frac{\pi}{\text{C.P.}}$$

$$\text{C.P.} = \frac{3\cdot1416}{\text{Diametral pitch}} \qquad \text{D.P.}$$

If the number of teeth in a gear is known or decided upon, and the diametral pitch is also known, the whole diameter or gear blank diameter is obtained by adding 2 to the number of teeth and then dividing the

number thus obtained by the diametral pitch. If the number of teeth is 40 and D.P. 10 as before:

$$\text{Gear blank diameter} = \frac{40 + 2}{\text{D.P.}} = \frac{42}{10} = \mathbf{4{\cdot}2\ in.}$$

If the number of teeth had been 40 and the diametral pitch 4, then the diameter of the gear blank is:

$$\frac{40 + 2}{4} = \frac{42}{4} = \mathbf{10\tfrac{1}{2}\ in.}$$

If the number of teeth and the gear blank diameter are given, the diametral pitch can be found by adding 2 to the number of teeth and dividing this number by the blank diameter:

$$\text{D.P.} = \frac{\text{N} + 2}{\text{Blank Diameter}}$$

If the number of teeth is 40 and blank 10½ in. diameter, then D.P. is:

$$\text{D.P.} = \frac{40 + 2}{10\frac{1}{2}} = \frac{42}{10\frac{1}{2}} = 4$$

or as above for 40 teeth, the blank diameter 4·2 in.; then:

$$\text{D.P.} = \frac{40 + 2}{4{\cdot}2} = \frac{42}{4{\cdot}2} = \mathbf{10\ D.P.}$$

If the pitch diameter and diametral pitch are given, the number of teeth in a gear can be obtained by multiplying the pitch diameter by the diametral pitch, e.g. if the diameter of the pitch circle of a gear is 10 in. and the diametral pitch is 4, then $4 \times 10 = 40$ = number of teeth; or if the pitch diameter say is 4 in. and D.P. = 10, then number of teeth $= 4 \times 10 = 40$.

i.e. Number of teeth N = D.P. × Pitch circle diameter

$$N = \mathbf{D.P.} \times d$$

If the whole diameter or gear blank diameter is given along with D.P. of gear, the number of teeth in the gear can be found as follows: multiply the blank diameter by D.P. and subtract 2 from the result to obtain N. If the blank diameter of gear is 10½ in. and D.P. 4:

$$N = (10\tfrac{1}{2} \times 4) - 2 = 42 - 2 = \mathbf{40}$$

i.e. there are 40 teeth of 4 D.P. in the gear.

Or, as in the other example in which the blank is 4·2 in. diameter and teeth 10 D.P.:

$$N = (4{\cdot}2 \times 10) - 2 = 42 - 2 = \mathbf{40.}$$

The thickness of the teeth at the pitch line is found by taking half the circular pitch or dividing the D.P. into 1·57.

$$\text{Tooth thickness} = \frac{\text{C.P.}}{2} = \frac{1{\cdot}57}{\text{D.P.}}$$

e.g. if the circular pitch of the teeth is 0·7854 and the diametral pitch is 4, dividing C.P. by 2 and 1·57 by 4 gives the thickness of tooth :

$$\text{Thickness} = \frac{0{\cdot}7854}{2} = \mathbf{0{\cdot}3927\ in.} = \frac{1{\cdot}57}{4} = \mathbf{0{\cdot}3927\ in.}$$

The whole depth of a tooth is obtained by dividing the diametral pitch into 2·157. The whole depth of teeth is approximately $\frac{11}{16}$ or exactly 0·6866 of the circular pitch.

Whole depth of tooth = C.P. $\times$ 0·6866 = $\frac{11}{16}$ C.P. approximately.

For a gear with teeth 10 D.P., the whole depth is:

$$\frac{2{\cdot}157}{10} = \mathbf{0{\cdot}2157\ in.}$$

$$\text{or} = 0{\cdot}6866\ \text{C.P.} = 0{\cdot}6866 \times \frac{3{\cdot}1416}{10} = 0{\cdot}6866 \times 0{\cdot}3142 = 0{\cdot}21572\ \text{in.}$$

From this it will readily be seen that the two methods yield the same result, viz. in this case, the full depth of tooth being equal to 0·2157 in.

To find the centre distance of two mating gears, add together the number of teeth in each gear, and divide half this sum by the diametral pitch. If, for example, two gears have 60 and 30 teeth respectively and the diametral pitch is 5, then centre distance of gears will be:

$$\tfrac{1}{2}(60 + 30) \div 5 = 45 \div 5 = \mathbf{9\ in.}$$

$$= \frac{90}{2 \times 5} = \frac{90}{10} = \mathbf{9\ in.}$$

that is, the centre distance of the two gears is 9 in.

Module.—The module or metric pitches are based on the relationship between the number of teeth in the wheel and the pitch line diameter, as in the case of the diametral pitches, but in module pitches metric measurement is used.

Module pitch is obtained by dividing the pitch diameter of the wheel in millimetres by the number of teeth in the wheel.

In standard gears the addendum is always 1 module in length.

If the diametral pitch of a gear is given, the module pitch or module (m) can be found by dividing 25·4 by the D.P.

Given the module, to find D.P. divide 25·4 by the module. Also to find the circular pitch, divide the module pitch by 8·085.

The Addendum is the distance from the pitch circle diameter to the crest or top of tooth.

Dedendum is the distance from the pitch circle diameter (P.C D.) to the bottom or root of tooth.

Clearance is the space left between the top of one tooth and the root circle of a mating gear.

As indicated earlier in this chapter, the tooth thickness is measured along the pitch line, but this of course is difficult to check. What is

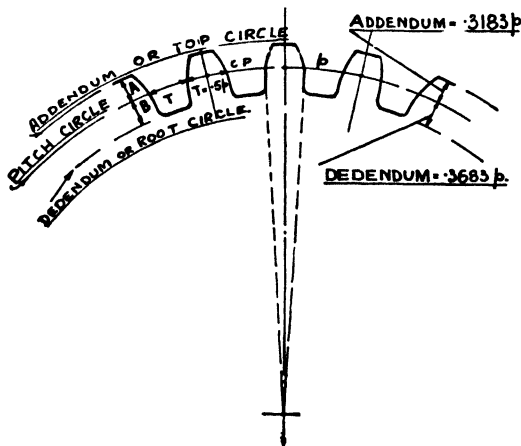
actually measured in cases where such is necessary, say when checking gears after manufacture, is the chordal distance, the straight line between the two points on the tooth flanks.

Base Pitch.—This is the circular distance (circular pitch) measured on the base circle.

Summarising the foregoing and putting the results down in simpler form, we have the following:

A = Addendum.
B = Dedendum.
C = Centre distance $= \frac{1}{2}(d + D)$ (see fig. 255) $= \frac{1}{2}(T_w + T_p) \div$ D.P.
D = Pitch diameter wheel $= \frac{T_w}{\text{D.P.}}$
d = Pitch diameter of pinion $= \frac{T}{\text{D.P.}}$
m = Module.
T_w = Number of teeth in wheel.
T_p = Number of teeth in pinion.
C.P. = Circular pitch
p = Circular pitch $\Big\} = \frac{\pi}{\text{D.P}}$ or $\frac{\pi}{\text{P}}$
D P. = Diametral pitch
P = Diametral pitch $\Big\} = \frac{\pi}{\text{C.P.}}$ or $\frac{\pi}{p}$
ψ = Pressure angle, or angle of obliquity.
t = Tooth thickness $= \frac{1}{2}p$.
c = Clearance = full depth — working depth.

The items mentioned above are indicated in the diagrams already mentioned and in Fig. 256.

FIG. 256—GEAR TERMS

Standard Spur Tooth Proportions

The main forms of teeth still in general use for spur gears are the 14½° and 20° pressure angle teeth and stub teeth, although the latter, originally intended to give greater strength, are now very little used, as the strength of steel gears is usually far in excess of the load permissible to give the least wear. The 14½° tooth also is disappearing in favour of the 20° tooth, as the gears cut to this form are more silent in operation, give better contact conditions, and undercutting in pinion teeth is reduced. The tooth forms mentioned above are shown in Fig. 257.

The 20° Pressure Angle Fellows Stub System applies to diametral pitches only, and the working depth and clearance used are those for

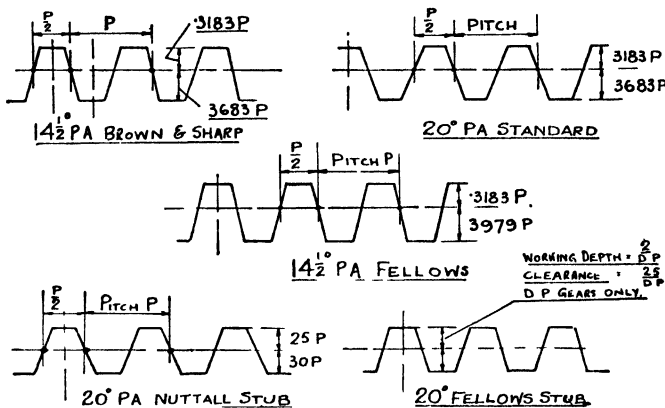



Fig 257—Gear Tooth Forms

2 D P. less for pitches under 4 D P , and for pitches 4 D.P. and over the clearance is for 1 D P. less. The pitches are therefore specified as $\frac{4}{5}$ pitch, $\frac{5}{7}$ pitch, $\frac{3}{4}$ pitch, etc., in which the numerator indicates the pitch and the denominator the pitch from which the tooth depth is based.

The standard tooth proportions are :

$$\text{Working depth} = \frac{2}{\text{D.P.}}\ ; \ \text{clearance} = \frac{0{\cdot}25}{\text{D.P.}}$$

The Addendum is equal to 0·3183 pitch, the Dedendum is equal to 0·3683 pitch, these terms being illustrated in Fig. 256.

Principles of Gear Production

As has already been mentioned, the Sunderland method employs a straight toothrack and generates a gear by a planing action. If one were to take a disc of plasticine or other plastic material and roll this backwards and forwards along a rack with sufficient pressure, the teeth of the rack would form teeth in the plastic. This is a simple way of illustrating the action of gear generation by the planing action of the rack, and is

precisely the action of the " Sunderland " system, because all the time the rack is planing the blank to produce teeth and spaces, the wheel is being rolled along the rack. In other words, the rack generates gear teeth.

In the machines for producing gears by this method, the cutter used is a section of a rack, the teeth of which are provided with cutting edges. The cutter is given a reciprocating motion across the face of the blank, and this cuts away the metal between the teeth being formed in the wheel. The cutter is gradually fed in to the full depth of tooth desired, and whilst this is proceeding, the gear blank is given a rotary motion, and the rack or cutter is traversed at a tangent, the motion of the gear blank and rack

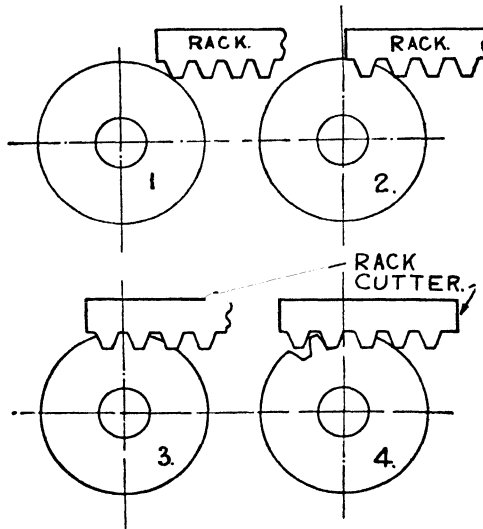



FIG. 258—PRINCIPLE OF GEAR SHAPING

being arranged by suitable gearing to act in unison on their respective pitch lines.

This relative motion is the same as if the rack and pinion were rolled together, and results in fresh parts of the blank being brought into contact with the rack, and thus teeth are generated, the form of which will gear or mesh perfectly with the same teeth as those of the cutter, or in other words, the gear will mesh with a rack having the same teeth as the cutter.

The principle of this method is illustrated in Fig. 258, and these sketches should be self-explanatory.

Fellows Generating Process

This method is one in which a circular cutter with cutting teeth of the form and pitch required on the blank revolves at the correct speed in

relation to the blank, i.e. it rotates in proper relation to the number of teeth in the cutter and the number of teeth to be cut in the blank. The cutter is also given a reciprocating motion of from between 200 to 450 strokes per minute.

The general principle of this method can readily be seen from the action of a cutter and blank as shown in Fig. 259.

As a tooth of the cutter rolls into the blank, it occupies different positions. The cutter tooth extends beyond the length of the gear tooth which it represents in order to cut deep enough into the tooth space to

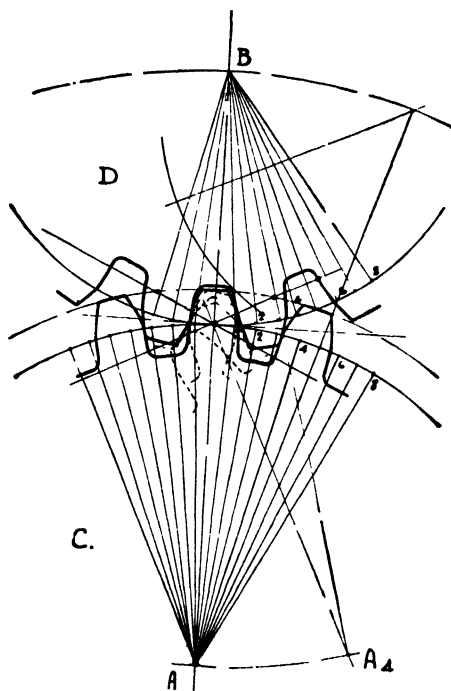



FIG. 259—GEAR-TOOTH GENERATION

form the necessary clearance. The corners of the cutter teeth are rounded or " cornered " to offset rapid wear, and in rolling into the blank, i.e. into and out of the tooth space, these rounded corners shape out the fillet and leave a substantial radius which strengthens the tooth.

To show the action of the above and similar methods in which a circular cutter rolls into a circular blank, draw out centre lines representing the centres of the cutter and blank marking centres *A* and *B*. When cutter *C* moves or rolls over blank *D*, the relative motion of these two parts can be represented. Draw in the pitch circles and divide the pitch circle of blank *D* into equal arcs by marking points 1, 2, 3, 4, etc., and the pitch line

of C into corresponding arcs 1^1, 2^1, 3^1, 4^1, etc., of equal length. Keeping C fixed in position, draw out a tooth of the generating cutter. The wheel D can now be rolled over C by bringing successive marked points to coincide, keeping the pitch circles in tangential contact. Trace the outline of the tooth for each position, and this will result in the generation of a tooth form. This will be clearer when it is seen that as the two pitch circles are rolled together, say until the points 4 and 4^1 come together, the centre of wheel C will be A_4, the tooth profile will be in position 4 and the contour of the tooth can be traced in. Repeating this a sufficient number of times will give a corresponding number of positions of the generating tooth profile. The tooth profile on D is the line enveloping all these successive positions of the generating tooth profile.

A similar method can be adopted to show the action of the straight-sided rack process of gear-tooth generation.

Referring to Fig. 260, which shows a line drawing of a cutter and partly

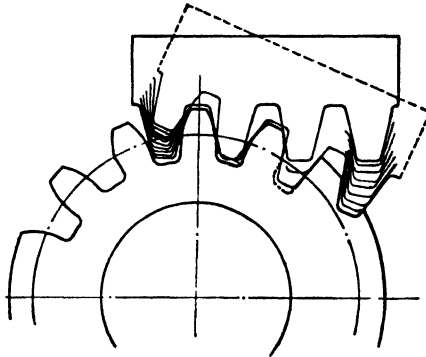



FIG. 260—GEAR-TOOTH GENERATION

cut blank illustrating how the tooth form is produced by successive strokes of the cutter, the student can illustrate this for himself by drawing down a gear blank with the pitch circle drawn in and making a cardboard template of the rack form. The template can now be placed in positions as indicated in Fig. 260 and the outline of the rack drawn in, giving the relative positions of the cutter and gear blank.

Production of Gears by Hobbing

This method of gear production is accomplished by means of a circular cutter of special design known as a hob (see Fig. 200, Chapter VI). The teeth on the hob lie on a spiral or helix, and the cutting faces are formed by spiral flutes or gashes. When mounted in the machine, the hob is set relative to the gear blank at an angle equal to the helix angle of the hob. The hob and gear blank are then rotated in correct relationship to each other, and this action results in the formation of a gear by a moulding

generating process. Wormwheels are invariably produced by this method.

Referring to Fig. 261, the principle involved in this method of gear production is clearly seen. Before the hob is gashed, it is in effect a type of worm, and a section taken normal to the teeth will present an imaginary straight-sided rack, which, with the rotary motion of the hob when cut-

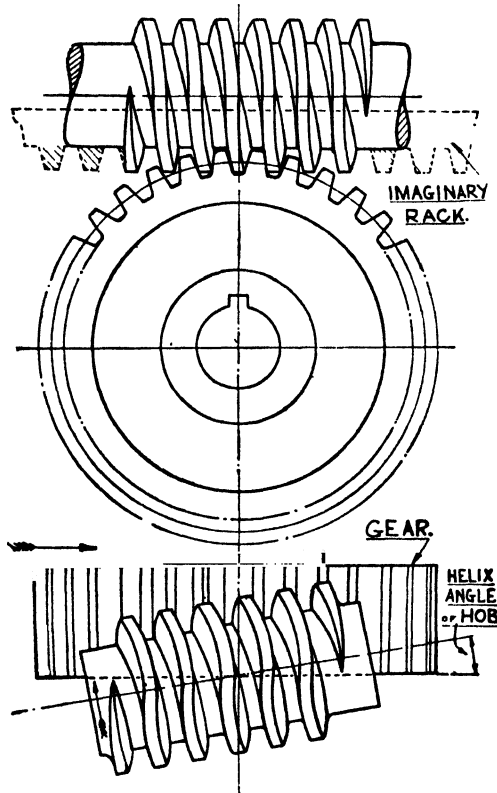



FIG. 261—GEAR HOBBING

ting, presents an endless rack for cutting the gear teeth. It should be remembered that the hob makes one revolution for each tooth in the gear being cut.

Production of Gears by Milling

This method employs a formed cutter, the teeth of which are shaped to the profile of tooth space required. The cutter is set on the milling machine arbor and the gear blank mounted between the centres of a dividing head, which is set to give the number of indexes required for

the gear to be cut, that is to say, the indexing is arranged so that the blank can be turned through the required amount each time to divide the periphery of the blank into the required number of teeth. Taking the

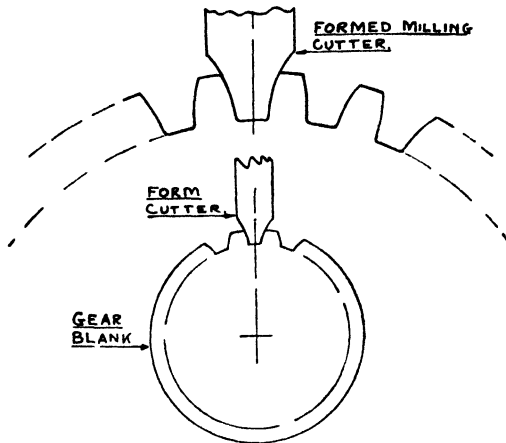



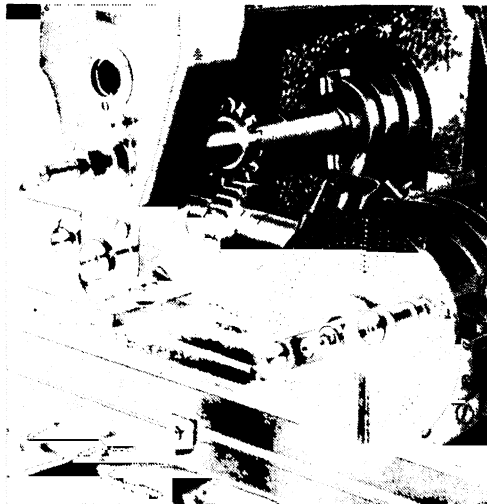
FIG. 262—PRODUCTION OF GEARS BY MILLING

Courtesy Cincinnati Milling Machines Ltd

FIG. 262A—MILLING GEARS

first cut, the formed milling cutter is fed across the face of the blank for spur gears whilst the blank remains stationary. For a gear with helical teeth, the blank is turned by the dividing head during the cutter travel to give the desired lead of helix of the gear teeth.

The method is illustrated in Figs. 262 and 262A, the latter being a set-up of a milling machine showing the teeth being cut in a gear blank.

Bevel gears can also be produced in a similar manner, but the production of gears by these methods is slow and only suitable where a small quantity or possibly special sizes are required. Otherwise the gear generating methods would be employed.

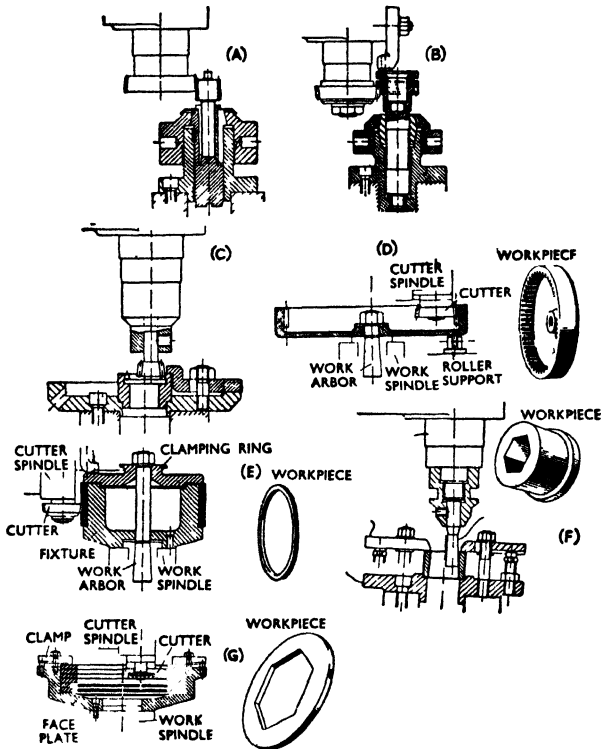
Modern methods of gear production employ gear generating machines

Courtesy Drummond Ltd.

FIG. 263—WORK PRODUCED BY MAXICUT GEAR SHAPER

of the multi-spindle type, in which a number of gear blanks are placed on fixtures mounted on a rotating table. The blanks receive a rotary motion about their own axes, and at the same time are revolved round on the table. With this planetary motion they meet a series of segmental cutters, and during one revolution of the table a gear is completed, and is being followed by others in varying stages of completion. The finished gear is removed from its location and a new one put in, i.e. a fresh blank is put in its place, and it continues in the manner just described, the cycle being continuous.

Typical of the type of gear-cutting machines is the Maxicut gear shaper; this machine is not confined to the production of gears and splines, but can be arranged to produce special shapes, such as cams, levers, hexagons, square and rectangular holes, and, in some cases, special machines can produce these holes with a taper as is encountered in certain dies.

A representative type of work produced by this machine is shown in Fig. 263, and a general view of the machine itself is shown in Fig. 264.

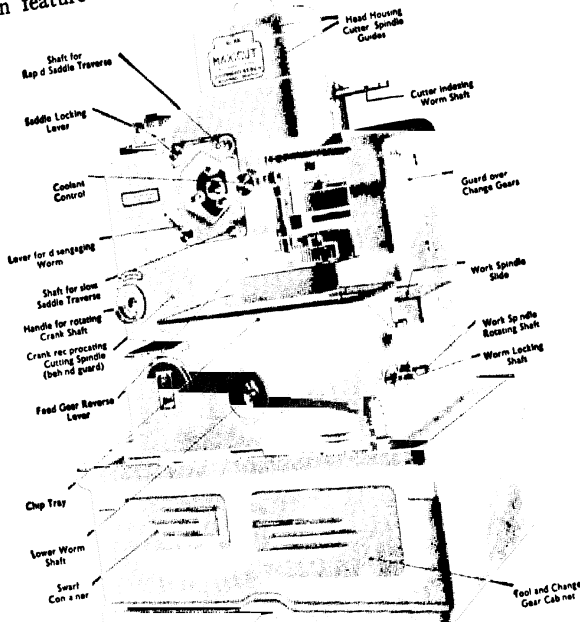
The main feature of this type of machine is the workhead which

THE No 2A MAXICUT HIGH SPEED GEAR SHAPER *Courtesy Drummond Ltd.*

FIG. 264

revolves the cutter at the correct speed for the gear to be produced. Change wheels are used to obtain these speeds, and since the cutter has to cut the teeth in the blank, a reciprocating motion is also imparted to the spindle and hence to the cutter. For gears with helical teeth, the cutter must have a helical or spiral motion in addition to the two motions mentioned above, and this is provided by suitable cylindrical-type cams. It is perhaps more usual for the cutting to be performed on the down-stroke of the cutter and the return on the up-stroke, although the machine works equally well in the reverse order with the cut on the up-stroke.

Whichever the method, the work and cutter are cleared on the return or non-cutting stroke, and the relieving mechanism is operated by a rack and quadrant, the latter being actuated by cams in the gearbox and pushrods.

Referring now to Fig. 263, the first illustration (A) indicates a solid-stem gear, 14 teeth of 14 D.P., made from mild steel. It is cut at a surface speed of 400 ft. per minute and a feed of 510. The cut in this case, as can be seen, is on the down-stroke. Cutting on the up or " pull stroke" is shown in (B), in which a double or cluster gear, 22 teeth, 3·25-in. pitch and 16° 30′ helix angle, is being cut, speed as for example (A) but a feed of 1,140 being used in this instance. Fig. 263 (C) and (D) show typical internal gear set-ups, (C) being a small gear with 15 teeth 10 D.P., whilst (D) shows a larger gear.

Multiple sets can be machined at one time, and (E) shows the arrangement of nine starter-ring gears being cut at once. Special shapes can also be cut by this machine, and (F) shows the setting for cutting a hexagonal hole (taper) in a flanged workpiece also shown.

As in the case of gears, so multi-settings of special shaped parts can be accommodated, and in (G) is seen an example of cutting six blanks with hexagonal holes in the workpiece shown.

The actual cutting operation as seen on a gear-cutting machine is shown in Fig. 265. Here a cluster gear, in which the top gear is 4¼ in. diameter, P.C.D. (pitch-circle diameter) 4 in., and lower gear 6¼ in. diameter, P.C.D. 6 in., is seen being cut. The teeth on this cluster gear are 8 D.P. in each case.

The relationship between cutter and work can be clearly seen in this illustration, as can the stream of lubricant between the cutter teeth and gear.

Finally, Fig. 265A is a capacity chart in which the cutter spindle is shown in two positions, one for cutting external gears and the other for cutting internal gears

Interference and Undercutting

The interference and undercutting of gear teeth is occasioned by the straight-sided rack and uncorrected circular cutter teeth. If the teeth of the circular cutter and straight rack are left with the form using the involute as generated, interference takes place, and this in turn leads to undercutting of the teeth in gears generated by them.

The condition of interference is indicated in Figs. 266 and 267, which show the condition and its effect for both circular cutters and straight racks.

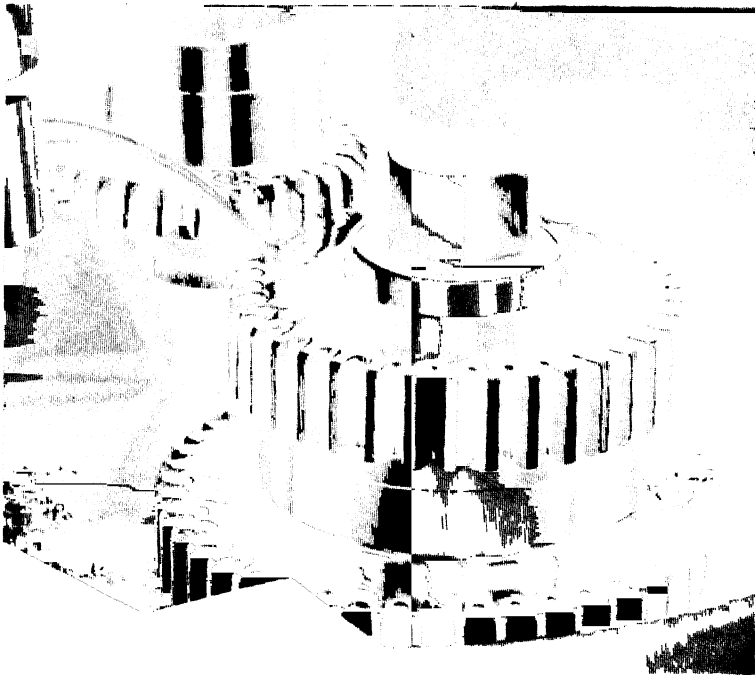
From the sketch it will be seen that there is interference caused by the uncorrected cutter tooth form. This is more pronounced in the case of the rack and pinion than in the case of two circular parts as a circular gear cutter and gear blank. The interference zone is shown by the shaded area in each of the two cases. The enlarged view shows the condition and also the corrected tooth outline for the rack teeth. For

Courtesy Drummond Ltd

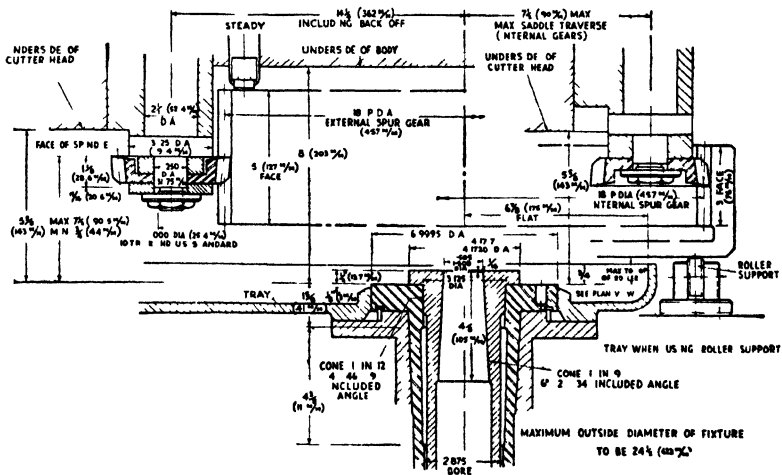
FIG 265—GEAR CUTTING ON MAXICUT SHAPER

Courtesy Drummond Ltd

FIG 265A—CAPACITY CHART

the circular cutter there is only slight interference, and the amount ot correction required is not as much as for the straight-sided rack.

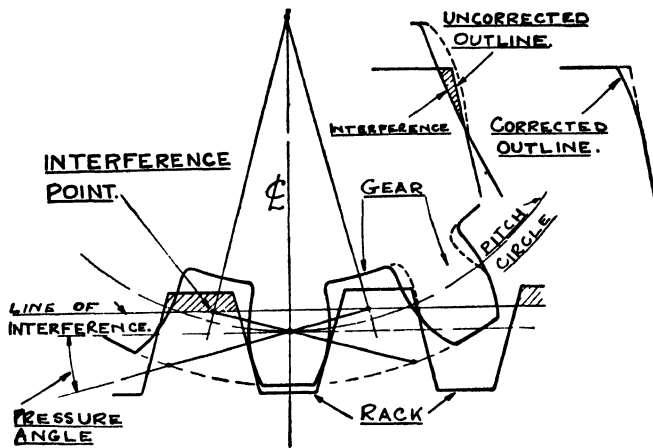



FIG. 266—INTERFERENCE OF GEARS

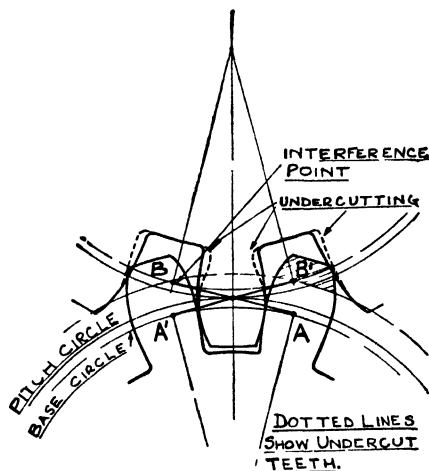



FIG. 267—GEARS

The corrected circular gear cutter has " cornered " teeth, that is, the part which causes interference is removed by " cornering."

These corrected or cornered teeth are used in the production of gears, which are thus protected from the fault of undercutting.

Bevel Gears

This type of gear is also an important one, and mention need only be made of mitre gears, crown wheels and pinions and drives for inclined shafts for the truth of this statement to be realised.

The points relating to bevel gears are shown in Fig. 268, which gives a typical bevel gear diagram, in which :

N_w = Number of teeth in wheel N_p = Number teeth pinion
D_w = Pitch diameter wheel D_p = Pitch diameter pinion
O_w = Outside diameter wheel O_p = Outside diameter pinion
A_w = Pitch angle wheel A_p = Pitch angle pinion
F_w = Face angle wheel F_p = Face angle pinion

T = Top angle
C = Circular pitch
H = Addendum (height above pitch line)

For the **wheel,** the following formulæ apply :

$$\text{Pitch diameter} = \frac{N_w . C}{3{\cdot}1416}$$

$$\text{Outside diameter} = D_w + (2H \times \cos A_w)$$

$$\text{Pitch angle, i.e. } \tan A_w = \frac{N_w}{N_p}$$

$$\text{Face angle, i.e. } \tan F_w = \frac{2 \sin A_w}{N_w}$$

Pinion

$$\text{Pitch diameter} \quad \frac{N_n . C}{3{\cdot}1416}$$

$$\text{Outside diameter} = D_p + (2H \times \cos A_p)$$

$$\text{Tan of pitch angle} = \frac{N_p}{N_w}$$

$$\text{Face angle} = A_p + T$$

$$\text{Tan of top angle} = \frac{2 \sin A_p}{N_p}$$

The above formulæ refer only to mitre wheels or bevel gears gearing at right angles—the gears for other angles, i.e. connecting shafts at other angles, require modification from the foregoing.

However, the general question of bevel-gear production can be seen in principle, and relates to most bevel-gear forms.

The main machines for bevel-gear production are the " Gleason " and " Bilgram " machines for generating bevel gears. Of these, the Gleason Bevel Gear Planing machines are more widely used and more generally known, and there are two main types : (*a*) copying from a master former, (*b*) generating the gear by motion of the machine parts and gear blank. There are also spiral gears (i.e. spiral bevel gears as used in hypoid gears for motor-car rear axles), and machines are available for cutting these which also work on the generating principle.

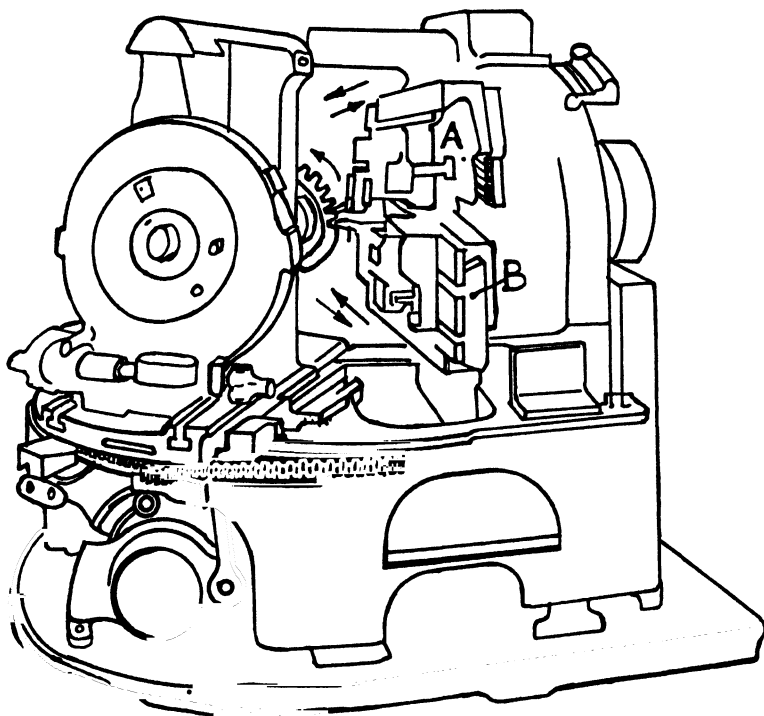
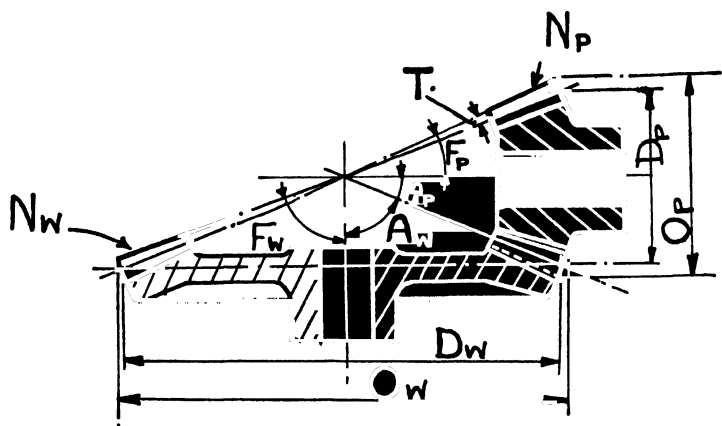



FIG. 268—BEVEL GEARS AND BEVEL GEAR GENERATING MACHINE

The purpose and scope of this book does not permit an involved study of gear generating machines. However, a brief description of the Gleason Automatic Bevel Gear Generator is given, which will suffice for immediate needs. Referring to Fig. 268, it will be seen that the tool slides *A* and *B*, which reciprocate continuously, as do the tools they carry, swing in to the gear blank and continue cutting until a full tooth depth has been reached. The tools now remain stationary, and by means of a cam and connecting rod the segment attached to the work spindle is caused to roll upwards, and as it is meshing with the master crown wheel or gear, it causes the tools to roll up also.

As the crown gear and segment roll together at the proper rate, the tools will generate on the gear blank a tooth which will be of correct profile, and which will run with the crown gear. Thus, all teeth are similarly cut—and wheels made by this process will mesh correctly. When one tooth has been cut, the turret tools swing out, the gear blank is indexed round and a new tooth is presented, and this is cut in the manner indicated—the turret and tools now feeding into the gear blank and cutting the next tooth. This process continues until the bevel gear is complete.

The machines have a set of segmental gears so that the correct rolling motion (see earlier part of chapter on involutes) can be obtained for gears of different pitch angles.

Finally, helical gears can be produced by similar methods, either spiral bevel gears or single helical, by obtaining the correct relative motion between the gear blank and cutter.

Double helical gears can be cut, the two sides being cut simultaneously when the teeth are staggered, the cutter working alternately on each tooth. If the gears do not have staggered or alternate teeth, then the double helical gears are usually cut in two operations—first one side, then the other.

Exercises on Chapter VIII

1. What are the forms of gear teeth used in present-day machinery?

2. Construct an involute curve for a base circle of 5 in. diameter.

3. Choose a suitable gear, and draw out the diagram showing the generation of a tooth form or space by a circular cutter.

4. Using the data of Question 3, draw out the tooth form, using a straight-sided rack.

5. What do you understand by the terms interference and undercutting? Illustrate your answers by suitable sketches.

6. Show how the straight-sided rack is used in the production of spur gears, and describe a machine using this principle of gear generation.

7. Describe the production of gears by the hobbing process.

CHAPTER IX

JIG BORING MACHINES

Jig Boring

THE subject of jig boring and jig boring machines is one closely linked with the work of the Production Engineer.

As with other machines, so with this type there are many makes and different designs and many accurate and ingenious mechanisms built into the machine in order to give the accuracy and fine limits on work calling for the use of a jig borer. As its name implies, it is used for work in connection with jigs, and is not, in the general sense, a production machine. It plays a very necessary and important part, however, in producing the jigs, fixtures and press tools to accurate dimensions and fine limits, and the jigs and press tools in turn are used for the quantity production of component parts.

Newall Jig Boring Machine

This machine employs a special system of rollers in a patented measuring system which is used to position the table. Table settings are controlled by a " Microlocator," using those rollers which are hardened and ground, and then given a chromium deposit before final lapping to size. The rollers are 1 in. diameter lapped to 1 in. diameter with an accuracy of within 0·00002 in. (two hundred thousandths of an inch). These rollers are carried in a train on the bed of the machine, and the microlocator is positioned on these rollers, one on either side of the table. On the underside of the microlocator is an inverted vee block, which locates the carriage between any two rollers ; and on each side of the machine is rigidly fixed a dial indicator which engages the micrometer spindle of the locator when the slide is moved up to it by means of the handwheel provided for the purpose. It will be seen, therefore, that when setting the table to a new position, the main inch measurements are obtained by merely moving the carriage to an alternative position along the train of rollers, and obtaining intermediate measurements by means of the micrometer head as desired. The head of the micrometer has a dial sufficiently large to enable tens of thousandths of an inch to be read with ease, and with this system the table of the jig boring machine and the work which it carries can be set within guaranteed limits of error of 0·0002 in. (two ten-thousandths of an inch) 2 tenths. This system of table setting is applied to both directions of the table movement, enabling the table to be set

in the horizontal plane in two directions at right angles to each other with an accuracy of 0·0002 in.

There are three models of the Newall Jig Boring Machine—No. 0, No. 1, and No. 2—using the above method of table setting. The amount of table travel for these machines is given in the following table. The No. 1 model, it will be seen, has a total longitudinal movement of 24 in., i.e. 12 in. either side of central position, and a cross traverse movement of 12 in. total, i.e. 6 in. on either side of the mid position.

TABLE 14

Model No.	*Total Long. Travel in in.*	*Cross Travel in in.*
0 (1520)	12 (10)	9 (10)
1 (2436)	24 (18)	12 (18)
2 (2442)	36 (24)	18 (24)

Models 0, 1, and 2 have been replaced by those shown in brackets and in addition automatic settings via punched card, tape and optical systems are now available.

Table Setting

The method of obtaining precise location of the work table is as follows. Firstly, the channel, train or rollers is sufficient to give the travel listed in Table 14. The microlocator has on the underside two vees, one at each end, one a plain vee, i.e. a vee with straight sides, and the other with convex surfaces. The upper surfaces of the rollers are exposed to receive the contact surfaces of the vees of the locator. The dial indicator, which is rigidly fixed on each slide, is connected to the spindle of the micrometer, that is to say, the dial indicator bears on the micrometer spindle through a rocking lever.

The setting of the table will be better appreciated by an example. Suppose it is required to bore a hole at a distance 3·2671 in. from an existing hole already bored in a workpiece. Firstly, the microlocator is adjusted to read zero after the dial indicator has been unclamped and moved as near to the table as possible. Now the microlocator is placed on the roller system as close to the rocking lever as location on the nearest roller will allow. Again adjust the dial indicator assembly until it registers zero with the rocking lever bearing on the microlocator anvil. The microlocator is now moved three rollers away from the table, i.e. a distance of 3 in., and the thimble of the microlocator is set to read 0·2671 in. and then locked in position. The table can now be moved backwards towards the microlocator until the rocking lever contacts the anvil and the dial indicator reads zero. Thus the table has been moved exactly 3·2671 in. Here it should be noted that the table settings obtained by this method are quite independent of the mechanical means employed to move the table, and, moreover, the dial indicator is in view of the operator whilst an operation is being performed. This being so, the

operator can observe the dial and detect any movement of the table which might occur during boring. The machine can also be used as a means of checking work already done on a jig borer or other machine.

The foregoing description of the work table location will be more clearly followed if the points to be observed are set down in order. For this purpose, suppose the table is to be moved 6·5432 in.

1. Unclamp the dial indicator assembly and move it as near to the table as possible.
2. Adjust the microlocator to read zero.
3. Place the microlocator on the roller system as close to the rocking lever anvil as location on a roller will allow.
4. Adjust the dial indicator assembly until it reads zero, the rocking lever bearing on the microlocator anvil.
5. Move the microlocator six rollers away, i.e. 6 in., or as many rollers as the setting required calls for.
6. Set the microlocator thimble to read 0·5432 in. (or whatever reading is required) and lock it.
7. Move the table towards the microlocator until the rocking lever contacts the anvil and the dial indicator reads zero.
8. The table has now been moved the exact amount, in this instance 6·5432 in., the movement being quite independent of the mechanical means employed to move the table.

The dial indicator is not used as a measuring device, its function being that of a sensitive telltale.

Spindle Setting

The setting of the spindle so that its axis is coincident with the machined datum edge of a piece of work may be accomplished by use of a setting bar which is inserted direct into the spindle bore. By moving the table to a position such that a ½-in. slip gauge can just be interposed between the 1-in. diameter cylindrical portion of the setting bar and the work, it will be known that the spindle axis is exactly 1 in. from the datum edge. Having adjusted the microlocator and dial indicator to zero, the former should be moved along one roller, i.e. 1 in., and the table brought up to give a zero reading on the dial indicator ; the spindle axis will then be coincident with the datum edge.

To compensate for any concentricity or malalignment of the setting bar relative to the spindle due to dirt on the locating surfaces, it is advisable to try in the slip gauge with the spindle in two positions approximately 180° apart, and the average between the two readings obtained on the table dial indicator should be taken.

To set the spindle axis concentric with the axis of a previously machined hole, the centralising locator should be used. This is held in the spindle collet. The table is moved so that the hole is approximately central with the spindle, and the positions of the dial indicator and contact finger

assembly adjusted, the latter being made to suit the hole diameter. With the spindle rotating at its lowest speed, the two table traverse handwheels should be adjusted until the needle of the rotating dial indicator does not deflect. The table can now be clamped in position and the microlocators and dial indicators set for zero.

A similar procedure is adopted should it be required to locate from some external circular surface, such as a spigot.

A general view of the No. 1 Newall Jig Borer is shown in Fig. 269, and the microlocator in Fig. 270, from which it will be possible to see the inverted vee and the method employed to position the microlocator on the roller train.

A later model of jig borer is the No. 2, which has power-operated slides, and a view of this machine is shown in Fig. 271. Whilst of later design and more recent construction, it employs the same basic principle for the table setting. A photograph showing a close-up view of the table of this machine is given in Fig. 272.

From this view the microlocators and roller system can be clearly seen, and also the controls for the table. As mentioned above, the slides are power-operated.

It is obvious that, in order to obtain the accuracy of work and fine limits required, the machine itself must be made with the greatest care and precision. This is the case with the Newall machine, and the methods employed can be understood when it is realised that the manufacture of the 1-in. diameter rollers for the positioning of the jig borer is such that the tolerance allowed on the overall dimension on a row of rollers just touching each other is 0·00005 in.

The base castings are planed on a " Bertram " planer, and the first cut is carried out at a speed of approximately 180 ft. per minute with a roughing feed of $\frac{1}{16}$ in. The roughing cuts are followed by a heat-treatment operation, and then a semi-finishing cut is taken, and this is followed by a finishing cut with a broad-faced tool, Ardaloy-tipped tools being used in the operations.

The bottom faces are machined first, and then the casting is placed on the planer table on these machined faces for location and the top faces machined. For the machining of the column casting, a horizontal boring and milling machine is used, and the vertical ways machined first by planing and these faces then used for locating the column casting whilst the base of it is milled. It is first rough machined, and then heat treated prior to finish machining to within scraping dimensions. During the operation the column casting is held in a special fixture which has guides machined on it for engaging the planed ways of the column.

The feedbox casting is machined in such a way that the bore for the spindle quill is used as a datum from which the guide ways and other surfaces are finished. The quill hole is fine bored to within 0·003 in. of the final diameter size required, and the bore then finished by lapping, the

FIG 271—NEWALL No 2 JIG BORER

FIG 269—NEWALL No. 1 JIG BORER

FIG 272 (*Below*)—MICRO-LOCATOR

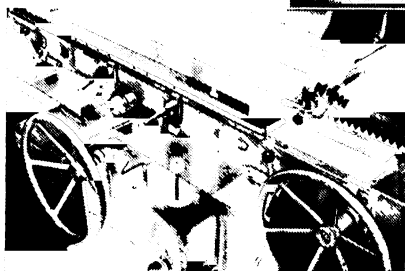
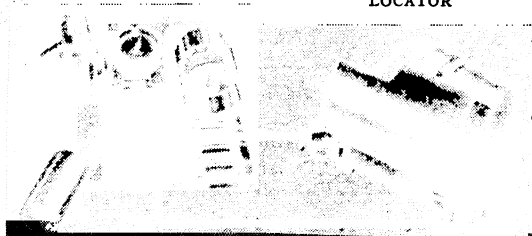



FIG. 272—CLOSE-UP VIEW OF NEWALL No 2

FIG 272(*a*)—MICROLOCATOR

(*Courtesy Newall Eng Co Ltd, Peterborough*)

tolerance allowed on the bore being only 0·0001 in., and this is obtained by a cast-iron lap of the split type. A cone is used to expand the lap as the lapping operation proceeds, and the grooves in the lap of helical form are treated with a mixture of oil and fine abrasive powder.

The guide ways of the feedbox casting are finally scraped to align them with the bore.

The quill, which is accommodated in the feedbox, is internally and externally ground on a Newall grinding machine to a tolerance of 0·0001 in. for the external diameter. The tolerance allowed for roundness is only 0·00005 in., for the bore diameter 0·0002 in. and roundness and concentricity 0·00005 in.

The various parts, such as crossways, etc., are also carefully checked, and the whole machine when assembled is checked over and a specimen piece machined up to test its performance. The finished jig borer is tested, acceptance tests for jig borers being given in the British Standards Institution (B.S.I.) Acceptance Test Charts.

This practical test includes the boring of a test plate, which is afterwards carefully checked, and a machine set up for this acceptance test is shown in Fig. 273.

In addition to the jig boring machines there are jig grinding machines. Of these, the Hauser Internal Jig Grinding Machine and combination Jig Boring and Jig Grinding Machine are noteworthy. This firm (Swiss) also manufacture a Precision Jig Boring Machine. The machines originally designed for the watchmaking industry, for small gears, and similar work, are capable of the most delicate drillings and borings, the 2A3 Hauser Jig Boring Machine being capable of drilling holes from $\frac{1}{64}$ in. diameter to $\frac{7}{16}$ in. diameter and boring holes to $\frac{7}{8}$ in. diameter, and with special tools to 2 in. diameter. The table movements are controlled by micrometer screws, which are entirely enclosed. The micrometer screws, provided with corrector bars, permit table settings within limits of 0·0001 in.

The spindle of the jig grinding machine, i.e. the grinding-wheel spindle, is driven by a compressed-air turbine working at a pressure of four atmospheres and giving speeds up to 40,000 r.p.m.

Methods of Dimensioning

In the production of jigs, fixtures, tools, and similar parts, with the dimensional accuracy available with precision jig boring and jig grinding machines, the location and positioning of holes, centres of curvature, radii, slots, and the like, may be determined by the method of co-ordinates.

There are three methods or systems of co-ordinate dimensioning:

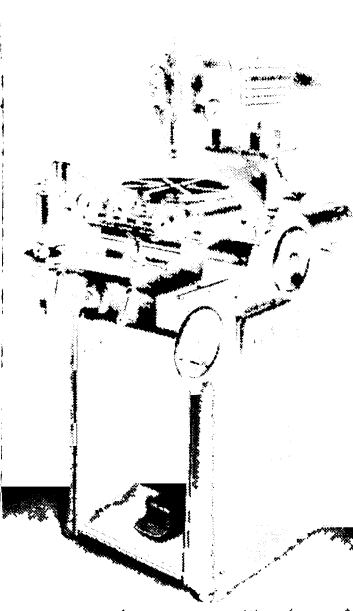
1. Focal Co-ordinates or Triangulation.—This method, usually referred to as triangulation, locates the position of a point by the distances from two principal points or foci. Suppose it is required to drill three

Courtesy Newall Eng Co Ltd, Peterborough

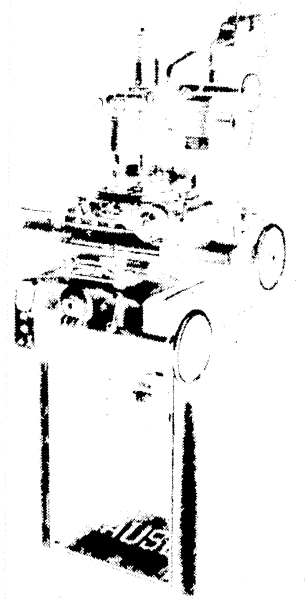
FIG. 273—BORE TEST FOR JIG BORER

Courtesy Hauser Ltd, per A C Wickman Ltd

FIG. 274—Top Right · HAUSER 2A3 JIG BORING MACHINE. FIG 275—Bottom Left HAUSER JIG BORER. FIG. 276—Bottom Right HAUSER JIG BORING AND GRINDING MACHINE

holes in a jig plate and no special apparatus is available, the first step is to drill a hole at the first point, and then finish to the required diameter. A flat button, perfectly calibrated, is now placed concentric with this

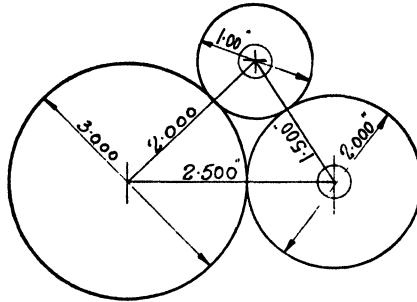



FIG. 277

hole, and fixed in position. Against this button, another button of size, such that the sum of the two radii is equal to the centre distance of the holes, is chosen, and this second button is then used to locate the second hole, which is now drilled. The second button can now be fixed, care being taken to ensure that it touches the first, which can now be removed. When this is done, the second button can be centralised and the hole then finished to size. The two buttons can now be replaced, and the third hole dealt with by choosing a button as before and finishing the hole to size.

This method can result in holes being drilled and finished with centre

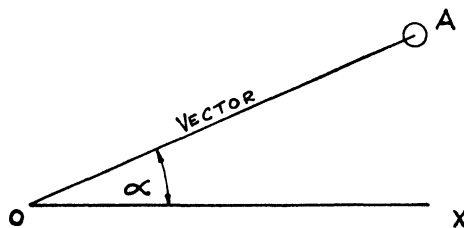



FIG. 278

distances to within 0·001 in. A typical arrangement of this is shown in Fig. 277.

2. Polar Co-ordinates.—This method of fixing the position of a point is by giving its distance from a fixed point or pole, and the angle contained between a fixed axis passing through the pole (polar axis) and the straight line joining the point to the pole.

The method is represented in diagram form in Fig. 278.

3. The third and most important method is that of **Rectangular Co-ordinates.** The reader may be familiar with this method under the heading of co-ordinate hole centres, and the method of dimensioning holes, etc., by this system is as follows. In algebra, it is well known that

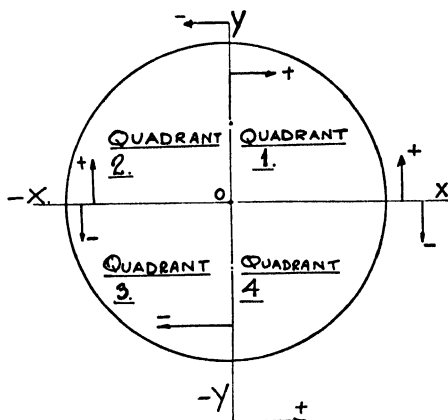



FIG. 279

triangles, centres of circles and points on the circumference of circles and also tangents are located by distances from the two axes x and y. A point is given as (8, 5), meaning that it is 8 units from the x axis and 5 units from the y axis. Now this is the method employed in rectangular co-ordinates, since the two distances can represent the two motions of the

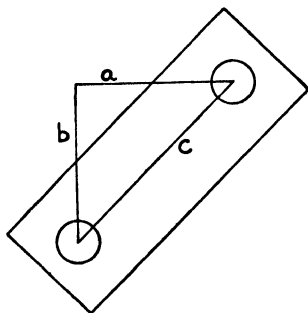



FIG. 280

jig borer table, and holes in the work located and positioned accordingly. The principle is shown in Figs. 279 and 280.

It will be seen that the distances from the x axis, or ordinates, are vertical measurements, and correspond with cross movements of the jig borer tables, and the distances from the y axis, or abscissæ, are horizontal measurements and correspond with the longitudinal movements

of the jig borer table, i.e. movements to the left or right of the centra position.

This method of determining positions by rectangular co-ordinates is the adopted and accepted method with most organisations. In using this method, the work may be considered as lying in one quadrant only, or may be in all four. Thus, if we set down two lines at right angles to represent the two directions of motion of the jig borer table, we can have *four* directions of motion from these axes:

Upwards taken as POSITIVE.
Downwards taken as NEGATIVE.
To the right taken as POSITIVE.
To the left taken as NEGATIVE.

(See Fig. 279.)

However, in general work the two axes are drawn and the work laid out in accordance with the requirements and the available travels of the jig borer table. The two axes are chosen in such a way that the centre of the work is at the middle of the path of each slide of the jig borer. If the travel of the table is 8 in. in each direction, the co-ordinates of the origin are chosen as $x = 4$ and $y = 4$.

For the travel of the Newall No. 1 Machine (see Table 14), the origin will be $x = 12$, $y = 6$.

As in the case of trigonometrical functions, a triangle may be located in any one of four quadrants, so it is with the co-ordinates used in jig boring, and the convention of signs applied to the ordinates and abscissæ is as applied to the former. For convenience and reference purposes this is given in Fig. 279.

Taking, now, an example, and applying it to the table travel of the Hauser 2A3 Jig Boring Machine with a longitudinal adjustment of 8 in. and an 8-in. adjustment of transverse slide, the location of the axes from the centre or mid-position of each slide of the jig boring machine will be 4 in.

Thus, if the work is as shown in Fig. 281, the corresponding distances from the two axes, horizontal H and vertical V, of the various hole centres can be tabulated as shown.

It has been argued that the two co-ordinates for each point should be placed on the component drawing, but this is not always practical, as it would undoubtedly complicate the drawing and overload it with figures and tend to errors. A detail of the part concerned can, of course, be made and so dimensioned if sufficient space is available. It is, however, much to be preferred for a table of the ordinates to be made as indicated in Fig. 281.

Another point which might be emphasised is the fact that very often parts are machined to limits that are not necessary. There is no useful purpose served in holding down the size of work to close limits where

this has no impact or influence on other parts or assemblies. For instance, fixing screws whose only duty is to hold parts together and whose location is determined mostly by the space available, need not be treated with the same precision as would be the case, say, for the centres of holes

Nº	H.	V.
1	4·0000	4·0000
2	4·0000	5·7500
3	2·4845	4·8750
4	2·4845	3·1250
5	4·0000	2·2500
6	5·5155	3·1250
7	5·5155	4·8750
8	3·5000	5·3515
9	4·5000	5·3515
10	4·7214	2·5854
11	4·7214	3·7034
12	4·0890	4·4665
13	3·6786	4·4151.
14	3·0520	4·2850
15	3·0502	3·8750
16	3·3454	3·5368
17	3·8911	3·5038.

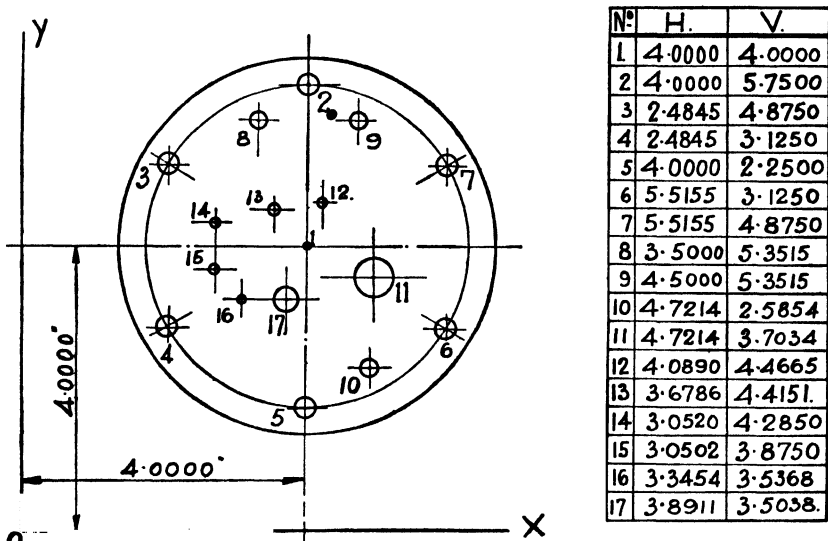



FIG. 281—JIG BORING—EXAMPLE ON RECTANGULAR CO-ORDINATES

for shafts or moving parts. It is, of course, necessary to discriminate carefully in this matter of deciding which parts are, and which parts are not, suitable for jig boring. Even where holes are jig bored, the dimensions for locating some of the hole centres need not be calculated by trigonometry ; such instances as those quoted above and others falling

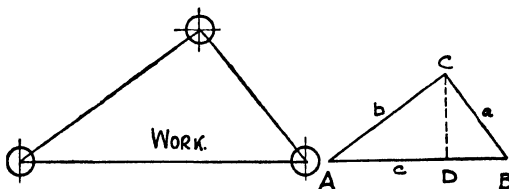



FIG. 282

within the same category can be bored to dimensions taken direct from the component drawing, in some cases by scaling.

For calculating the ordinates for a hole whose centre is to be in definite relationship to two others, the procedure can be as follows :

Referring to the sketch in Fig. 282, we have :

For examples of this kind, where three sides of the triangle formed by joining the centres are given, the problem can be solved by calculating

the lengths of CD and DB. Since holes A and B are on the same line, A can be bored, the table moved along to bring hole B under the boring spindle, and hole B finished Then by moving the table to the right a distance DB and forward a distance CD, the centre of hole C will be obtained, and this can then be bored.

To find the values of CD and DB from the three sides given will involve trigonometry to find one of the angles, and since only the sides are given, these must be used to find the angle desired. This can be accomplished by using the formula ·

$$\tan \frac{A}{2} = \sqrt{\frac{(S-b)(S-c)}{S(S-a)}}$$

Where $S = \frac{1}{2}$ sum of the sides $= \frac{1}{2}(a+b+c)$, or a variation to find one of the remaining angles B or C.

Thus for the case just cited, it would be better to find first the angle B

$$\tan \frac{B}{2} = \sqrt{\frac{(S-a)(S-c)}{S(S-b)}}$$

Then the two lengths CD and DB are found from :

$$CD = a \sin B$$
$$DB = a \cos B$$

To illustrate the point, a numerical example will be considered. Referring to Fig. 282, let it be required to drill three holes in the positions shown, the centres of which lie at the three corners of a triangle the sides of which are

$$a = 1{\cdot}067 \text{ in.}$$
$$b = 1{\cdot}600 \text{ in.}$$
$$c = 2{\cdot}170 \text{ in.}$$

First a perpendicular is dropped on to line AB, meeting it in point D.

Here $S = \frac{1}{2}\{2{\cdot}17 + 1{\cdot}6 + 1{\cdot}067\} = \frac{4{\cdot}837}{2} = 2{\cdot}4185$ in.

$$S - a = 2{\cdot}4185 - 1{\cdot}067 = 1{\cdot}3515 \text{ in.}$$
$$S - b = 2{\cdot}4185 - 1{\cdot}6 = 0{\cdot}8185 \text{ in.}$$
$$S - c = 2{\cdot}4185 - 2{\cdot}17 = 0{\cdot}2485 \text{ in.}$$

We can now find either the angle A or B.

Choosing A, we have :

$$\tan \frac{A}{2} = \sqrt{\frac{(S-b)(S-c)}{S(S-a)}}$$
$$= \sqrt{\frac{(0{\cdot}8185)(0{\cdot}2485)}{2{\cdot}4185(1{\cdot}3515)}} = 1{\cdot}3968$$

i.e. $\frac{A}{2} = 14°$

and $A = 28°$

$$\text{Now } CD = b \sin A = 1{\cdot}6 \times 0{\cdot}4695 = 0{\cdot}75125 \text{ in.}$$
$$DA = b \cos A = 1{\cdot}6 \times 0{\cdot}8829 = 1{\cdot}41264 \text{ in.}$$

We now have the distances required, and when hole A has been bored, the hole B on the same line can be bored by moving the table along to the left a distance 2·1700 in. Now hole C can be located by winding back the table a distance 2·17 — 1·41264, i.e. 0·75736 in., and then moving it in a cross direction 0·75125 in.

To calculate the angle B, and find the figure 0·75736 first, would eliminate the step just taken of finding this dimension from 2·17 — AD.

Another example of the same kind worked out in relation to the

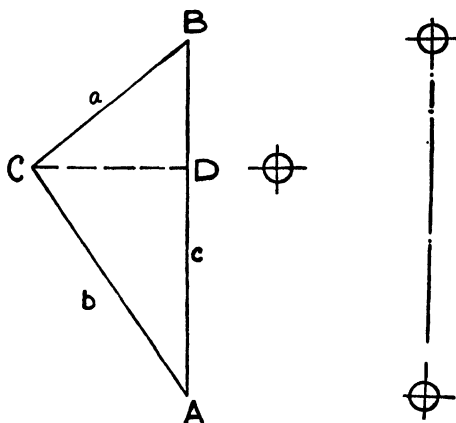



Fig. 283

Hauser Jig Boring Machine, with a table travel of 4 in. in each direction from the centre, should round off this particular type of problem.

Let the problem be to drill three holes in positions as shown in Fig. 283, in which hole C is to be in the relationship given to A and B. If a, b, and c are the corresponding sides with values as given :

$$a = 1{\cdot}8100 \text{ in.}$$
$$b = 2{\cdot}0000 \text{ in.}$$
$$c = 3{\cdot}0000 \text{ in.}$$

$$\text{Now } S = \tfrac{1}{2}\{1{\cdot}81 + 2 + 3\} = \frac{6{\cdot}81}{2} = \mathbf{3{\cdot}4050 \text{ in.}}$$

$$S - a = 3{\cdot}4050 - 1{\cdot}8100 = 1{\cdot}5950 \text{ in.}$$
$$S - b = 3{\cdot}4050 - 2{\cdot}0000 = 1{\cdot}4050 \text{ in.}$$
$$S - c = 3{\cdot}4050 - 3{\cdot}0000 = 0{\cdot}4050 \text{ in.}$$

Using the formula already given to find the angle B, we have :

$$\tan \frac{B}{2} = \sqrt{\frac{(S-a)\,(S-c)}{S(S-b)}}$$

$$= \sqrt{\frac{1{\cdot}595 \times 0{\cdot}4050}{3{\cdot}405 \times 1{\cdot}405}}$$

$$= 0{\cdot}3675$$

$$\therefore \frac{B}{2} = 20^\circ\ 10'\ 35''$$

$$\text{and angle } B = \mathbf{40^\circ\ 21'\ 10''}$$

$$\begin{aligned}
\text{Now distance } CD &= a \sin B \\
&= 1{\cdot}81 \sin 40^\circ\ 21'\ 10'' \\
&= 1{\cdot}81 \times 0{\cdot}64754 \\
&= \mathbf{1{\cdot}1719\ in.}
\end{aligned}$$

$$\begin{aligned}
\text{Distance } BD &= a \cos B \\
&= 1{\cdot}81 \cos 40^\circ\ 21'\ 10'' \\
&= 1{\cdot}81 \times 0{\cdot}76206 \\
&= \mathbf{1{\cdot}3793\ in.}
\end{aligned}$$

If proof were needed, the problem could be checked back as follows. Taking the triangles BCD and ACD, we can use the ordinates just found, and from them re-calculate the sides of the triangles.

The horizontal component of $C = 4{\cdot}000 - 1{\cdot}1719 = 2{\cdot}8281''$
The vertical component of $C = 4{\cdot}000 - 1{\cdot}3793 = 2{\cdot}6207''$
Thus distance $BD = 4{\cdot}000 - 2{\cdot}6207 = 1{\cdot}3793$

$$\begin{aligned}
\text{Side } BD &= 4{\cdot}000 - 2{\cdot}6207 = 1{\cdot}3793 \\
CD &= 4{\cdot}000 - 2{\cdot}8281 = 1{\cdot}1719 \\
AD &= 2{\cdot}6207 - 1{\cdot}0000 = 1{\cdot}6207
\end{aligned}$$

From formula for right-angled triangle :

$$\begin{aligned}
a &= \sqrt{BD^2 + CD^2} \\
&= \sqrt{1{\cdot}3793^2 + 1{\cdot}1719^2} = \sqrt{1{\cdot}9024 + 1{\cdot}3733} \\
&= \sqrt{3{\cdot}2758} \\
a &= \mathbf{1{\cdot}80999\ in.} = \mathbf{1{\cdot}8100\ in.} \\
b &= \sqrt{AD^2 + CD^2} \\
&= \sqrt{1{\cdot}6207^2 + 1{\cdot}1719^2} \\
&= \sqrt{2{\cdot}6266 + 1{\cdot}3733} \\
&= \sqrt{4{\cdot}000} \\
b &= \mathbf{2\ in.}
\end{aligned}$$

The verification yields a figure for a which is not absolutely correct in so far that it gives a value of 1·80999 ; but this is of course 1·81 to all intents and purposes.

As previously mentioned, the jig borer can be used for measuring distances; for example, the centre distance of holes already drilled or bored.

There are two methods:

(*a*) By setting the piece on the machine table parallel with one of the axes of movement locating one hole under the spindle and taking the readings. Then moving the table until the second hole is under the spindle and taking the readings. This will necessitate accurately lining the holes up with a dial gauge held in the spindle in some machines, or viewing the two edges of the holes on the centre line in each of the two readings. The edges of the holes of the piece shown in **Fig. 284** can be viewed through the microscope, as in the Hauser machines, and this also checks the hole diameters at the same time as the centre distance.

In the example in question the slide is first moved until the measuring wire of the microscope coincides with the edge of one of the holes and the

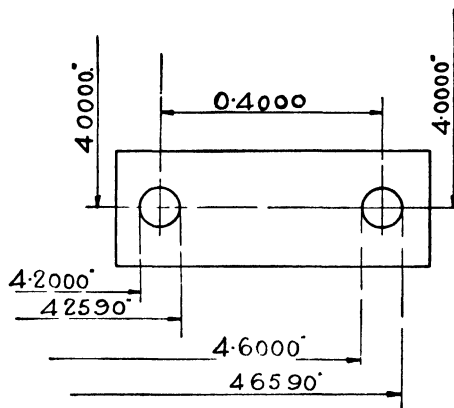



FIG. 284

reading taken. This is **4·2000 in.** Now the slide is moved until the measuring wire picks up the other side of the hole, when the reading is 4·2590 in. The slide is now moved over until the first edge of the next hole touches the measuring wire and the reading now is 4·6000 in., and when the next edge of the hole comes under the microscope measuring wire the reading is 4·6590. From these the centre distance is obtained thus:

Outer distance =	4·6590	Inner distance =	4·6000
	− 4·2000		− 4·2590
	0·4590		0·3410

$$\text{Centre distance} = \frac{0\cdot4590 + 0\cdot3410}{2} = \mathbf{0\cdot4000\ in.}$$

(*b*) In this alternative method the plate can be fixed in any position and then the measuring wire brought to the centre of the first point, measuring by the edges as in the previous case. The position is now

read for the two slides for this first point, and then the method is repeated for the second hole and, in each case, the horizontal x and vertical y co-ordinates thus obtained.

The difference between the horizontal co-ordinates $= a$.
The difference between the vertical co-ordinates $= b$.

$$\text{Now } C = \sqrt{a^2 + b^2}$$

$$\begin{array}{ll} x' = 3{\cdot}9650 \text{ in.} & a = x'' - x' = 4{\cdot}2780 - 3{\cdot}9650 \\ y' = 3{\cdot}5720 \text{ in.} & \qquad\qquad\quad = \mathbf{0{\cdot}3130 \text{ in.}} \\ x'' = 4{\cdot}2780 \text{ in.} & b = y'' - y' = 3{\cdot}8210 - 3{\cdot}5720 \\ y'' = 3{\cdot}8210 \text{ in.} & \qquad\qquad\quad = \mathbf{0{\cdot}2490 \text{ in.}} \end{array}$$

Substituting these values for a and b in the expression

$$C = \sqrt{a^2 + b^2}$$
$$C = \sqrt{0{\cdot}3130^2 + 0{\cdot}2490^2}$$
$$C = \mathbf{0{\cdot}39996 \text{ in.}}$$

The above readings were made on the same plate which gave the 0·4000 in. reading in method (a). Thus the error is 0·4000 — 0·39996 = 0·00004 in. (four hundred thousandths of an inch $= \frac{4}{100000}$).

By general approximation, the dimension to four figures = 0·4, the same as before, and the dimensions are within the guaranteed limits of 0·0001 in.

Thus, it will be seen that the jig borer can be used, not only to bore holes within the required limits of accuracy, but may also be used to check over holes already machined by some other method.

Exercises on Chapter IX

1. Describe the operation of any jig boring machine with which you are familiar.

2. When dimensioning a component for machining on a jig borer, what method must be adopted ?

3. Three holes spaced at the three corners of a triangle are to be jig bored. If the base of the triangle is $1\frac{1}{4}$ in. long and horizontal, and the other two sides are 1 in. and $\frac{3}{4}$ in. respectively, sketch the layout and give the sizes of buttons used for drilling these holes on a lathe.

4. If, in Question 3, the holes were spaced as follows, base of triangle = 4·34 in., other two sides 3·2 in. and 2·134 in., calculate the rectangular co-ordinates for drilling these holes on a jig borer.

5. If, in Questions 3 and 4, the holes were spaced on a triangle ABC, in which the sides are $a = 0{\cdot}905$ in., $b = 1{\cdot}00$ in., $c = 1{\cdot}500$ in., and c is vertical, calculate the necessary distances for moving the jig borer table in order to spot the three holes, i.e. calculate the ordinates.

6. Show how holes which have already been bored in a workpiece may be checked on a jig borer. Select a suitable numerical example to illustrate your description.

CHAPTER X

MACHINE TOOL DESIGN

THE trend in modern machine tools is to ever-increasing speeds, particularly in grinding machines, where the spindles for fine-bore work are being revolved at high speeds. Naturally, the high speed is accompanied by fine feeds and light cuts, with the result that a high finish is obtained.

The advent of high-frequency current has permitted many new approaches to existing problems, and resulted in improvements in heat treatment, local tool-heating problems and high spindle speeds as mentioned above. Machines with grinding-wheel spindles revolving at 40,000 r.p.m. and speeds of 60,000 r.p.m. are used for bore finishing, which can be ground to 1 or 2 micro-inches. The prefix " micro " meaning millionth part, the surface finish is between 0·000001 in. and 0·000002 in.

Projected speeds of 100,000 r.p.m. for grinding-wheel spindles indicate the future development, and no doubt machines running at these speeds will be available in the future. Special motors are used for driving these spindles in conjunction with a converter, and the normal supply is changed from the standard 50-cycle supply to a higher frequency, which is then fed to the motor driving the spindle head gear.

Such machines as these need careful attention to detail when laying the foundations, and the finer limits of surface finish are obtained from foundations of absorbent material and not from rigid types, although the main foundation is made of concrete to support the machine, the other material, which may be compressed cork, being applied at the support points. By this means the vibration is damped out and the spindle is enabled to produce the finish mentioned above.

Foundations are important in respect of machine layout, and it is better, wherever possible, to use a three-point layout. The principle is indicated as follows: first it must be remembered that the makers test the bed and machine alignments, and usually workpieces are " run off " with the bed level in both longitudinal and transverse directions. Consequently, the machine should be set up in the same manner. A good check for the machine would be to have a 12-in. length of bar protruding from the collet or chuck, and the end of this tested when revolving at a normal speed. This will check the spindle and bearings (see Fig. 285). For the bed levelling, this can be done by using a precision spirit level

FIG. 285—CHECKING SPINDLE ALIGNMENT

FIG. 286—Right. SENSITIVE SPIRIT LEVEL

Courtesy Alfred Herbert Ltd

FIG. 287—CHECKING ALIGNMENT OF BED WAYS

(see Fig. 286), checking up the bed by laying the level near the spindle nose both transversely and longitudinally, and again near the end of the bed both in front of and behind the capstan slide, and in front of and behind the turret in a turret lathe. Checking up the bed and levelling in this way will avoid " cross winding " and the consequent stresses in the bed and machine parts. To complete the check up the machine should produce a piece turned from tools located in the turret, and a piece turned with tools located in the saddle, i.e. cross slide or square

Courtesy Alfred Herbert Ltd.

FIG. 288—CHECKING LATHE BED—SPIRIT LEVEL ACROSS WAYS

toolpost (Fig. 285). In checking the machine position, the support wedges should be adjusted so that the spirit-level readings are correct in all positions. The method is shown in Figs. 287 and 288, together with the position of the wedges as shown in Fig. 289. Once the machine is properly levelled, its accuracy depends largely upon the spindle and its bearings, which in turn rely on correct setting, clearances and lubrication.

Bearings.—These fall mainly into two classes, plain and ball and roller bearings.

Plain bearings, when properly designed and bedded to the spindle, form an excellent support, but are not capable of adjustment apart from rebedding by scraping. Also, this type of bearing requires a lot of fitting

in the first instance, and relies on a film of oil for its successful operation. The correct clearances must be provided for the oil film, and here we have one point of danger: when the machine is left standing, the oil drains out of the bearing chamber and allows the spindle to rest on the bearing surface, giving metal to metal contact. This condition is present when the machine is started up (unless provision is made to counteract it), and the metal to metal contact results in scored bearings if the machine is run under load before the oil film has been built up. The conditions obtaining are shown in Fig. 290 (A), (B), (C), and (D), in which the spindle or shaft is shown at (A), when the machine has been left to

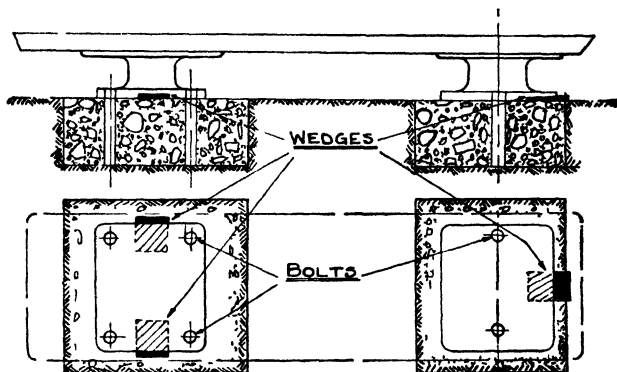



FIG. 289—MACHINE FOUNDATIONS

stand, allowing the oil to drain away, and then the result as the spindle begins to rotate, drawing the oil in the manner shown into the bearing chamber (B). The resultant bearing pressure, which is the vector sum of the load and the oil pressure when this latter is fully developed, is also indicated and the sketches are self-explanatory.

Another difficulty with plain bearings is the provision for taking axial or thrust loads. This condition is met by using a cone-shaped portion on the spindle, but here again the initial fitting of the bearing to the shaft is laborious. Nevertheless, it must be remembered that many good machines have operated on these bearings. The ideal plain type of bearing for negotiating both radial and axial loadings is one developed on the principle elaborated by "Schiele," and many of the plain bearings approximate to this, or incorporate a portion of the form of bearing propounded by Schiele. The idea was developed in connection with a footstep bearing, but it is equally applicable to horizontal bearings where thrust (axial) and radial loadings have to be carried.

It is obvious that, as the distance from the centre of a shaft increases, the rubbing speed also increases, and this is clearly seen in the case of a footstep bearing which for a 5-in. diameter shaft will increase from zero

to 15·7, or from 0 to $2\pi R = 2\pi \times 2\frac{1}{2} = 5\pi$, which is the value given. Similarly, for a 6-in. diameter shaft the velocity varies from 0 to $2\pi R = 2\pi \times 3 = 6\pi = 18{\cdot}852$, the actual value of the velocity depending on the number of revolutions per minute which the shaft makes.

Considering a shaft which must negotiate both radial and thrust loading, the form of a bearing to accommodate these loads can be developed in the following manner.

Let OA be the radius of the thrust face $= R$. On the centre line OB,

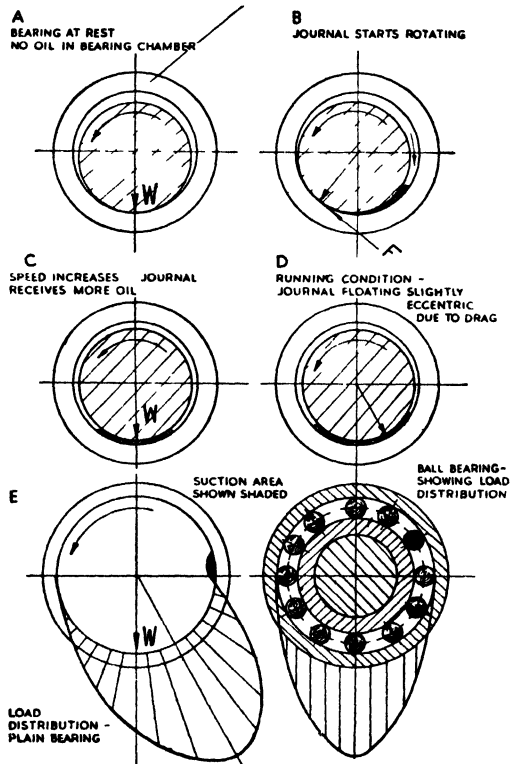



FIG. 290—BEARINGS

mark off a number of divisions 1, 2, 3, etc. Now join point No. 1 on the centre line to the outside point A of the flat bearing surface. On this line $A1$ mark off a distance equal to the radius OA or R. Point 2 on the centre line is now joined to this point just made by marking off the radius R on line $A1$, and again the distance R is marked off. By continued repetition of this process a series of points marked off on the lines thus constructed is obtained, and a curved surface, as shown on the right-hand side of Fig. 291, results. On the other side of the diagram the curve has

been lined in, showing the ideal form of a bearing which will take loads from all directions as indicated by the arrows drawn normal to the various construction lines, and it will readily be seen that loads varying between horizontal and vertical directions can be negotiated by this form of bearing. That is to say, it will take both radial and thrust loads. It is, however, difficult to produce, but approximations to this curve can be made, and some machines actually have bearings, portions of which conform to this curve, whilst some grinding machines have had spindles made on the prin-

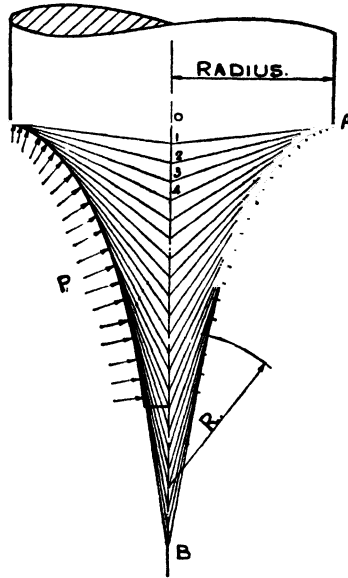



FIG. 291—" SCHIELE " CURVE

ciple outlined above. The approximation can be made by taking two or three tangents to the curve at selected points, and by this means tapered portions can be easily obtained to form a bearing surface, and the tapers can be much more readily produced in practice than the developed curve.

The best bearing for the conditions of radial and thrust loading is the taper roller bearing, which, by virtue of its construction, will take any combination of radial and thrust loading.

Moreover, the taper bearing is capable of being preloaded, so that all play can be taken out of it and maximum accuracy of the spindle supported by it obtained thereby. Lubrication in the sense and manner as applied to the plain bearing is not required, the main function of the lubricant being to prevent rust and pitting of the contact surfaces and dissipate heat.

Bearing Clearances

As stated in an earlier part of this chapter, the plain-type bearing runs in a film of oil, and to accommodate this, bearing clearances must be provided. The allowances which are made to cover this contingency, i.e. the allowances for oil between the shaft and the journal, are usually given as so many thousandths of an inch on the shaft diameter to give the bearing bore. The following table gives the usual allowances for this, and from the values given it will be seen that the allowance of one to two thousandths radial clearance for small bearings is confirmed by these figures, since for journals from ⅜ in. diameter to 3¾ in. diameter the clearances 0·001–0·002 in. give the figures 0·002 in. and 0·004 in., as in Table 15.

TABLE 15

ALLOWANCE FOR OIL BETWEEN SHAFT AND JOURNAL

Shaft or Journal Diameter	*Allowance on Diameter*
in.	*in.*
⅜–1	0·002
1⅛–2½	0·003
2⅝–3½	0·004
3⅝–4½	0·005
5	0·006
5½	0·007
6	0·008
6½	0·009
7	0·010
7½	0·011
8	0·012

In connection with this question of lubrication, many and varied experiments have been conducted and special oils developed as a result. This is particularly the case in respect of high or extreme pressure lubricants which have been developed to withstand the high loading conditions in gear drives where the pressure between two faces of driving teeth ruptures the oil film and allows metal to metal contact. There are many machines in existence for testing the load-carrying capacities of oils, the main principle of which is to arrange two metal surfaces and separate them by a film of the oil to be tested. Predetermined loads can be applied, and definite rates of velocity, both of which can be varied to give any desired value, and for a given value say of rubbing speed the load is increased until the film breaks down and allows the metals to rub together. This results in a scored surface, and from the scratch produced details of the wearing properties of the materials can also be established. Obviously the load at which the oil film breaks down

is the absolute maximum, and from it a recommended safe load for the oil can be determined.

In addition to the load-carrying properties of oils, the reduction in power to drive a bearing lubricated by the oil can be determined, as clearly the lower the value of the coefficient of friction, μ, the more efficient is the bearing.

The value of the coefficient of friction μ can be found for a bearing as follows:

If S be the speed or velocity of rubbing in feet per minute,

P the bearing load,

A the projected area of the bearing = diameter $\times$ length = $D.L$

p = bearing pressure in lb. per square inch = $\frac{P}{A}$

$$\text{then } \mu = \frac{C\sqrt{S}}{p}$$

$$\mu = C\frac{\sqrt{S} \times D \times L}{P}$$

C is a constant which varies with the grade of oil, and is usually between 0·2 and 0·3 for most oils used for bearing lubrication, the nearer value for general purposes being 0·28.

Thus, for a bearing 3 in. diameter and 6 in. long, running at 450 r.p.m. and carrying a load of $1\frac{1}{2}$ tons, the value of μ will be:

$$\mu = \frac{0{\cdot}28\sqrt{S} \times 3 \times 6}{P}$$

$$= \frac{0{\cdot}28\sqrt{362} \times 18}{1{\cdot}5 \times 2240}$$

$$= \frac{5{\cdot}04\sqrt{362}}{3360}$$

$$= \frac{5{\cdot}04 \times 19{\cdot}02}{3360}$$

$$= 0{\cdot}02854$$

$$= \mathbf{0{\cdot}029 \text{ approximately.}}$$

$$\text{Here } S = \pi DN$$

$$= \frac{\pi \times 3 \times 450}{12}$$

$$S = \frac{450\pi}{4}$$

$$= 112{\cdot}5\pi$$

$$= \mathbf{362 \text{ ft./min.}}$$

That is, the coefficient of friction $\mu = 0{\cdot}02854$, or working out the value of p the pressure in lb. per square inch:

$$p = \frac{P}{A} = \frac{P}{\text{D.L}} = \frac{3360}{18} = \textbf{186·6 lb./sq. in.}$$

$$\mu = \frac{0{\cdot}28\sqrt{S}}{p}$$

$$= \frac{0{\cdot}28\sqrt{362}}{186{\cdot}6}$$

$$\mu = \textbf{0·02854 as above.}$$

This second method can be used where a given bearing pressure is involved. It will also be seen that for a given load or pressure the size of the bearings can be determined from the bearing area, which is always

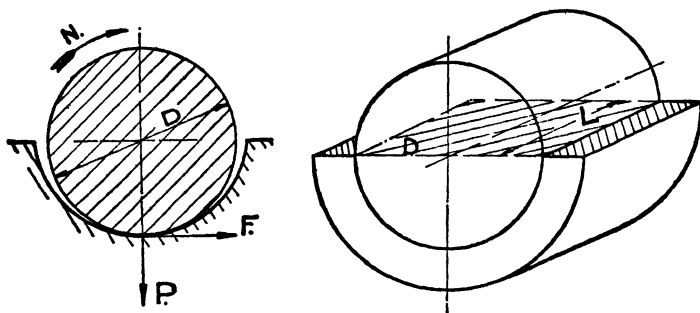



Fig. 292—Plain Bearing

the projected area given by the product of the diameter times length. The proportions usually are that L is greater than D, the minimum condition being that $L = D$, but very often the length is $2\text{–}2\frac{1}{2}D$.

The power lost to friction can be found when the coefficient μ is known.

Referring to sketch (Fig. 292), if D is the diameter, μ the coefficient of friction, P the load and N the revolutions per minute, then since in one revolution the bearing will move a distance equal to πDN, the force due to friction $F = \mu P$.

$\therefore$ work lost to friction,

i.e. work done in overcoming frictional resistance $= \pi DN\,F$

$= \pi DN\,\mu P$ ft./lb.

and power lost to friction $= \dfrac{\pi DN\mu P}{33000 \times 12}$

Example.—Find the h.p. lost to friction in the bearings of a flywheel weighing 5 tons if it makes 150 r.p.m. and the bearing is 6 in. diameter. Take $\mu = 0{\cdot}028$.

$$\begin{aligned}
\text{The friction force } F &= \mu P \\
&= 0{\cdot}028 \times 5 \times 2240 \\
&= 224 \times 1{\cdot}4 \\
&= \mathbf{313{\cdot}6\ lb.} \\
\text{Journal speed} &= \pi DN \\
&= 6\pi \times 150 \\
&= 900\pi \\
&= \frac{2827{\cdot}8}{12} \\
&= \mathbf{235{\cdot}5\ ft./min.} \\
\therefore \text{work done} &= 235{\cdot}5 \times 313{\cdot}6 \text{ ft.-lb./min.} \\
\text{and H.P.} &= \frac{235{\cdot}5 \times 313{\cdot}6}{33000} \\
\text{H.P.} &= \mathbf{2{\cdot}23}
\end{aligned}$$

The problem is worked out in the manner indicated to show the value of the bearing speed and friction force. It could, of course, have been done directly by substituting the values in the expression given, viz.:

$$\begin{aligned}
\text{H.P.} &= \frac{\pi DN\ \mu P}{33000 \times 12} \\
&= \frac{\pi \times 6 \times 150 \times 0{\cdot}028 \times 11200}{33000 \times 12} \\
\text{H.P.} &= \mathbf{2{\cdot}23}
\end{aligned}$$

i.e. practically $2\frac{1}{4}$ h.p. is used in overcoming the effects of friction.

It is obvious, from the expression for the value of μ, that speed is a contributing factor, and as is well known, μ varies with speed.

The value of the coefficient of friction for ball and roller bearings is as follows:

Friction in ball bearings $\mu = 0{\cdot}0015$ at 250 r.p.m.
Taper roller bearings $\mu = 0{\cdot}0021$ at 250 r.p.m.

From the above it will be seen that for a taper roller bearing which is capable of taking both thrust and radial loadings the friction is less than $\frac{3}{10}$ of 1 per cent. Comparing the friction force F for say 1,000 lb. for the taper bearing:

$$\begin{aligned}
F &= \mu P \\
&= 0{\cdot}0021 \times 1000 \\
F &= \mathbf{2{\cdot}1\ lb.}
\end{aligned}$$

Taking the value of μ found in the example using the expression:

$$\mu = \frac{C\sqrt{S}}{p} \text{ giving } \mu = 0{\cdot}02854$$

$$\begin{aligned}
F &= 0{\cdot}02854 \times 1000 \\
\therefore F &= \mathbf{28{\cdot}54\ lb.}
\end{aligned}$$

From this the comparison is clearly shown, the force due to friction being 2·1 lb. for the taper bearing as against 28·54 lb. for a plain bearing. Of course the bearings vary, and these figures should not be taken as representative of all bearings. In point of fact, the value of μ should have been found for 250 r.p.m. to be a strict comparison.

This would give:

$$\mu = \frac{0{\cdot}28\sqrt{196{\cdot}6}}{186{\cdot}6}$$
$$= 0{\cdot}0212$$

This new value of μ gives the following comparison: Friction force, taper bearing 2·1 lb. for 1,000 lb. load, and 21·2 lb. for plain bearing under the same conditions; whilst for a ball bearing the friction force would be 1·5 lb.

The effect of the varied value of friction with the type of bearing has another aspect in the heating effect, which is, of course, an important feature of successful bearing operation. The friction force multiplied by the rubbing speed in feet per minute gives the number of foot-pounds of mechanical work used to overcome the friction, and from the heat equivalent of this an estimated rise in temperature can be obtained.

At 250 r.p.m. for a 3-in. diameter bearing, the speed $S = 196{\cdot}6$ ft./min.

Taper.—By work done against friction $= 2{\cdot}1 \times 196{\cdot}6$

$= 412{\cdot}86$ ft.-lb./min.

Heat equivalent $= \dfrac{412{\cdot}86}{778}$

$=$ **0·53 B.Th.U. per minute**

Plain.—By work against friction $= 21{\cdot}2 \times 196{\cdot}6$

$= 4167{\cdot}92$

Heat equivalent $= \dfrac{4168}{778}$

$=$ **5·35 B.Th.U. per minute**

It will be remembered that the British Thermal Unit (B.Th.U.) is the amount of heat required to raise the temperature of 1 lb. of water through 1° F. Thus, the heating effect of the friction force is such that it would raise 5·35 lb. of water through 1° F.

Let us further suppose that the above bearing is to be cooled by oil whose specific heat is 0·6, and that the temperature rise is limited to 10° F. on account of space left for the oil film. Then from this data it will be possible to find the amount of oil which must be fed to the bearing to maintain these limiting conditions.

Since the quantity of heat which a body possesses is the product of its mass, specific heat and temperature :

$$Q = \text{Weight} \times \textit{specific heat} \times \textit{temperature rise}$$
$$Q = W \times x \times t$$
$$5{\cdot}35 = W \times 0{\cdot}6 \times 10$$
$$W = 0{\cdot}893 \text{ lb. of oil per minute}$$

Thus it can be seen that for this particular bearing running at 250 r.p.m. with 1,000 lb. load, the quantity of oil required per minute to maintain the temperature to within 10° F. of normal will be 0·893, or 53·58 lb./hour.

Now this 250 r.p.m. is not a high speed, and in most cases the speeds of bearings are much higher, with a resulting increase in friction and hence the need for more oil to cool the bearing, and so the oil is fed into the bearing chamber by an oil-feed pump which pumps cool oil in and extracts the heated oil, which is passed to a cooler or reservoir, to which it gives up its heat. The conditions for any bearing problem can be treated in a similar manner by substituting the variables in the expressions already used, and by this means several factors can be determined. Thus, for a given load, operating speed and temperature rise of a bearing, the quantity of oil required can be determined, and from this the size of the oil pump, the usual allowances or margins also being considered.

The bearing loads are determined (*a*) for plain bearings by a figure which gives the maximum allowable pressure per square inch of projected area ; and (*b*) for ball and roller bearings by load-carrying capacities, which the manufacturing companies give in relation to their bearings. These load-carrying capacities are to be found in lists alongside the various sizes of bearings available.

In the case of taper roller bearings, the load carried can be either all radial, all thrust, or a combination of the two. Factors for combining a thrust and radial load into an equivalent radial load are given, and then from this a bearing of the right capacity can be chosen for the amount of equivalent radial load.

The load-carrying capacity of a roller bearing is related to the " life " of the bearing when in actual service, and as in cutting tools, speed is a limiting factor. The bearing capacity is based on a speed of 500 r.p.m. and modification factors employed for use with other speeds. Some typical problems follow, showing the manner in which a roller bearing selection may be made.

The load ratings of Timken bearings are based on 500 r.p.m. and 500 hours' life expectancy. For other conditions of speed the load capacity varies, and to find the equivalent capacity, or convert the loading conditions to a suitable figure, modification factors must be used. These factors are (1) speed factor, (2) life factor, and (3) application factor ; this latter deals with the type of service which the bearing is to undertake. Since the life factor and application factor are more or less constant for a given problem, they are replaced by a " service factor."

Required rating at 500 r.p.m.

$$= \frac{\text{Calculated load} \times \text{Life factor} \times \text{Application factor}}{\text{Speed factor}}$$

$$\text{Service factor} = \text{Life factor} \times \text{Application factor}$$

$$\text{Combined factor} = \frac{\text{Service factor}}{\text{Speed factor}}$$

Thus, taking these into account, the bearing rating capacity required at 500 r.p.m., is given by:

Capacity required = Calculated resultant load × Combined factor. The factors are given in tables in the company's handbook.

For a wheel, such as a farm cart or similar implement, suppose the load is centrally applied and two bearings carry a load of 1,500 lb. at a speed of 10 m.p.h. and the wheel is 24 in. diameter:

$$\text{First find r.p.m. of wheel} = \frac{\text{Feet per minute}}{\text{Wheel circumference}} = \frac{10 \times 5280}{60 \times \pi \times 2}$$

i.e. Wheel r.p.m. = **140**
Speed factor from Tables = 1·297
Service factor from Tables = 3·5

$$\text{Combined factor} = \frac{3{\cdot}5}{1{\cdot}297} = \mathbf{2{\cdot}7}$$

Referring to the sketch (Fig. 293) the 1,500 lb. is taken by two equally spaced bearings, each carrying 750 lb.

∴ Required bearing capacity = 750 × 2·7
= **2,025 lb.**

Now by reference to the tables in the bearing catalogue a suitable bearing can be selected having the above capacity and of the diameter to suit the axle. It is obvious that, if the bearings are not spaced equally on either side of the wheel centre-line, one bearing, the nearer, will carry more load than the other and the two loadings must be worked out. If the original design had the bearings spaced 3 in. each side of the centre line giving 750 lb. on each bearing, then for a spacing of say $1\frac{1}{2}$ in. and $4\frac{1}{2}$ in. from the centre line the loads will be:

$$\frac{4\frac{1}{2}}{6} \times 1500 = 1{,}125 \text{ lb., and } \frac{1\frac{1}{2}}{6} \times 1500 = 375 \text{ lb.}$$

These must be multiplied by the combined factor of 2·7 in each case, and then the most suitable bearing for these loads obtained by reference to the tables as already indicated, choosing bearings of the required bore and outside diameter for the wheel. In machine-tool work the bearing problems are mostly linked up with gear drives, worm drives or belt drives, and typical examples of these will follow.

1. Spur Gears, 0° Mesh.—Taking a standard case of 5 h.p. at 250 r.p.m., teeth 14° 30′ pressure angle, gear $5\frac{3}{4}$ in. P.C.D., pinion $1\frac{1}{2}$ in. P.C.D., and other details as shown in sketch (Fig. 293):

$$\text{Speed factor} = 1{\cdot}231$$

$$\text{Service factor} = 2{\cdot}5$$

$$\text{Combined factor} = \frac{2{\cdot}5}{1{\cdot}231} = 2{\cdot}03$$

$$\text{Tangential force on input gear} = \frac{\text{H.P.} \times 33000 \times 12}{\pi \text{D.N.}}$$

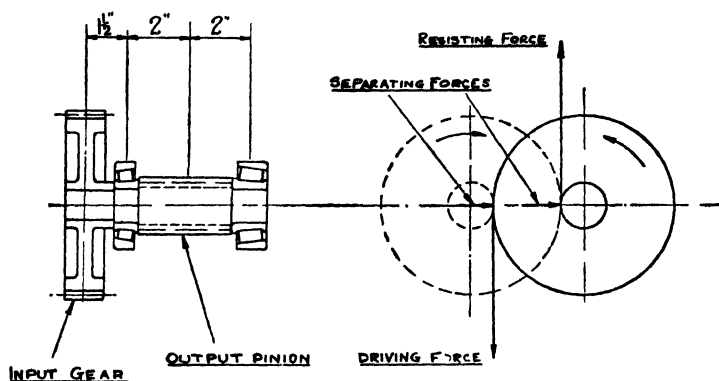



Fig. 293—Gears, 0° Mesh

Note: $\frac{33000 \times 12}{\pi}$ is constant and equal to 126,000, which can be used in these calculations.

$$\text{Tangential force} = \frac{5 \times 126000}{5{\cdot}75 \times 250} = \mathbf{438\ lb.}$$

$$\text{Tangential force on output pinion} = 438 \times \frac{\text{P.C.D. gear}}{\text{P.C.D. pinion}}$$

$$= 438 \times \frac{5{\cdot}75}{1{\cdot}5} = \mathbf{1{,}680\ lb.}$$

$$\text{Separating force on input gear} = 438 \times \tan \text{ of pressure angle}$$

$$= 438 \times \tan 14\tfrac{1}{2}°$$

$$= 438 \times 0{\cdot}258 = \mathbf{113\ lb.}$$

$$\text{Separating force on output pinion} = 1680 \times \tan 14\tfrac{1}{2}$$

$$= 1680 \times 0{\cdot}258 = \mathbf{433\ lb.}$$

∴ Resultant load on bearing *A*

$$= \sqrt{\left(438 \times \frac{5{\cdot}5}{4} - 1680 \times \frac{2}{4}\right)^2 + \left(113 \times \frac{5{\cdot}5}{4} + 433 \times \frac{2}{4}\right)^2}$$

$$= \mathbf{440\ lb.}$$

Resultant radial load on B

$$= \sqrt{\left(438 \times \frac{1\cdot5}{4} + 1680 \times \frac{2}{4}\right)^2 + \left(113 \times \frac{1\cdot5}{4} - 433 \times \frac{2}{4}\right)^2}$$

$= \mathbf{1{,}020\ lb.}$

Capacities of bearings required at 500 r.p.m.:

$$\text{Bearing } B = 1020 \times 2\cdot03$$
$$= \mathbf{2{,}070\ lb.}$$

On bearing A the resultant thrust load must be obtained as follows:

$$\text{Resultant thrust} = \frac{0\cdot34 \times \text{radial load } B}{K_B}$$

$$K_B = \frac{\text{Radial rating } B}{\text{Thrust rating } B} = \frac{2790}{1390} = 2\cdot01$$

$$\therefore \text{Resultant thrust load} = \frac{0\cdot34 \times 1020}{2\cdot01} = \mathbf{173\ lb.}$$

The equivalent radial load of the combined loads on A:

$$\text{Equivalent load} = 0\cdot66 \times \text{radial load } A + K_A \times \text{Thrust load}$$
$$\text{Assume } K_A = 1\cdot5$$
$$\text{Then load} = 0\cdot66 \times 440 + 1\cdot5 \times 173$$
$$= \mathbf{549\ lb.}$$

Required capacity rating at 500 r.p.m. = 549 × 2·01 = **1,115 lb.**

These two figures, viz. 2,070 lb. and 1,115 lb., are the bearing loads at 500 r.p.m., and suitable bearings should be chosen for the shaft diameter and bearing outside diameter.

2. Spur Gears, 90° Mesh.—Taking the same conditions as above, 5 h.p., 250 r.p.m., etc., and dimensions as in Fig. 294:

$$\text{Speed factor} = 1\cdot231$$
$$\text{Service factor} = 2\cdot5$$
$$\text{Combined factor} = 2\cdot03$$

$$\text{Tangential force on input gear} = \frac{126{,}000 \times 5}{5\cdot75 \times 250\pi} = \mathbf{438\ lb.}$$

Tangential force on output pinion = **1,680 lb.**

These figures are the same as previous example.

Resultant radial load A

$$= \sqrt{\left(438 \times \frac{5\cdot5}{4} + 433 \times \frac{2}{4}\right)^2 + \left(1680 \times \frac{2}{4} + 113 \times \frac{5\cdot5}{4}\right)^2}$$

$= \mathbf{1{,}290\ lb.}$

Resultant radial load B

$$= \sqrt{\left(438 \times \frac{1\cdot5}{4} - 433 \times \frac{2}{4}\right)^2 + \left(1680 \times \frac{2}{4} - 113 \times \frac{1\cdot5}{4}\right)^2}$$

$= \mathbf{800\ lb.}$

Required radial rating A

$= 1290 \times 2\cdot03 = \mathbf{2{,}620\ lb.}$

Resultant thrust load B

$$= \frac{0\cdot34 \times \text{radial load } A}{K_A} = \frac{0\cdot34 \times 1290}{2\cdot01} = \mathbf{218\ lb.}$$

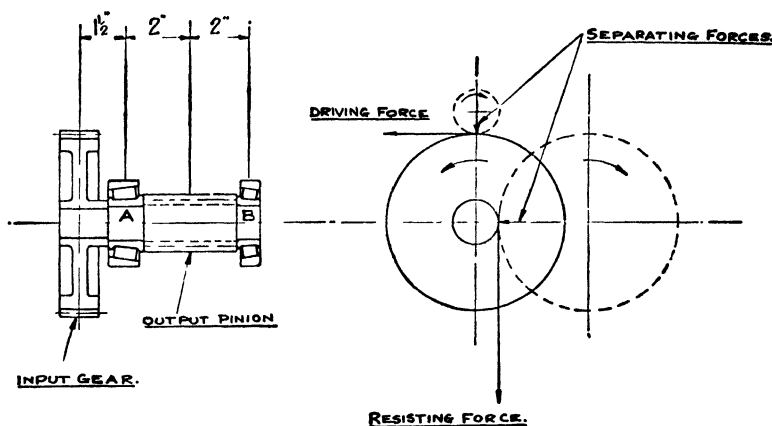



FIG. 294—GEARS, 90° MESH

Equivalent radial load of combined loads on B

$= 0\cdot66 \times \text{radial load } B + K_B \times \text{Thrust load}$

$= 0\cdot66 \times 800 + 1\cdot5 \times 218$

$= \mathbf{855\ lb.}$

Assume $K_B = 1\cdot5$.

Required radial rating $= 855 \times 2\cdot03 = \mathbf{1{,}735\ lb}$

The bearings with suitable bore and outside diameter dimensions with capacities of 2,620 lb. for bearing A and 1,735 lb. for bearing B will be selected from lists in the manufacturer's catalogue. It should be noted that the value of K_B, assumed as 1·5 for the tentative selection, will vary with the bearing selected according to the ratio of Radial/Thrust capacity, but since the difference is small and the capacities given allow a range of choice of bearing, the selection based on the above is satisfactory. Should a problem present any difficulty, reference to the bearing manufacturer is always advisable.

There is one remaining case for spur gears, that of 180° mesh. Taking

the same values as the two previous cases, the problem is identical as far as finding the resultant loads.

Resultant load A

$$= \sqrt{\left(438 \times \frac{5\cdot5}{4} + 1680 \times \frac{2}{4}\right)^2 + \left(113 \times \frac{5\cdot5}{4} - 433 \times \frac{2}{4}\right)^2}$$

$= \mathbf{1,445\ lb.}$

Resultant load B

$$= \sqrt{\left(438 \times \frac{1\cdot5}{4} - 1680 \times \frac{2}{4}\right)^2 + \left(113 \times \frac{1\cdot5}{4} + 433 \times \frac{2}{4}\right)^2}$$

$= \mathbf{723\ lb.}$

The capacity for bearing A = 1445 × 2·03 = **2,930 lb.**

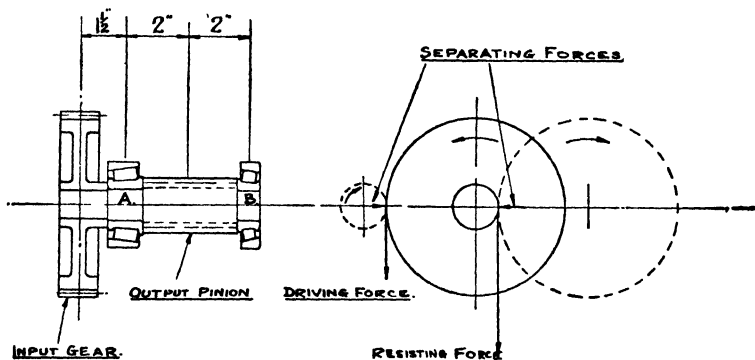



FIG. 295—GEARS, 180° MESH

For bearing B the capacity is arrived at in the same manner as that employed in the two previous cases and gives a figure of 956 × 2·03 = **1,940 lb.**

If helical gears are used instead of spur gears, there will be an additional thrust due to the helix angle of the teeth. If the last case, that of 180° mesh, be taken and the exact conditions duplicated on a set of helical gears instead of spur gears, the conditions would be identical up to the finding of the resultant load on the bearings.

Suppose the helix angle to be 17°.

Thrust from input gear = 438 × tan of helix angle
= 438 tan 17 = 438 × 0·305 = **132 lb.**

Thrust on output pinion = 1680 × tan 17 = 1680 × 0·305
= **513 lb.**

Thrust load on bearing B = 513 − 132 = **381 lb.**

The "hand" of the helix, i.e. right or left hand, and the direction of rotation will determine the direction of the thrust, and incidentally the

bearing which has to withstand this added thrust. With double helical gears this thrust is neutralised.

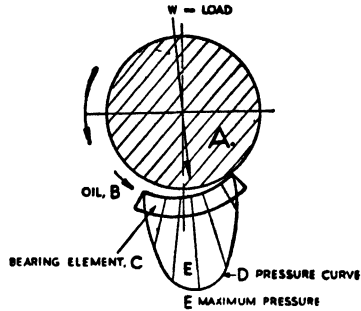
The various types of bearings used in machine-tool construction are

Courtesy Cincinnati Milling Machines Ltd.

FIG. 296—THEORY OF OIL FILM AND BEARING SHOE

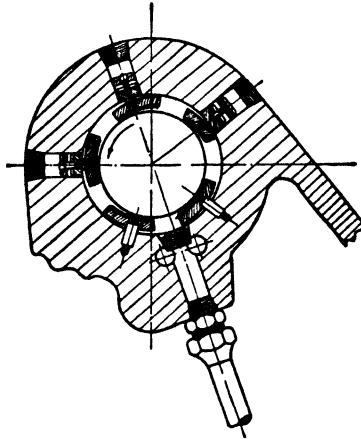
either plain bearings or a special adaptation of the plain bearing, ball bearings, parallel roller bearings, or taper roller bearings. Some of the plain-type bearings take special precautions in regard to the oil film, and

Courtesy Cincinnati Milling Machines Ltd.

FIG. 297—FILMATIC BEARING

Note.—The entire bearing chamber is maintained under a pressure substantially above atmospheric.

one such is the Cincinnati " Filmatic " bearing, which has a number of bearing shoes as shown in Figs. 296 and 297.

In Fig. 296 the journal A, when rotating in a bearing element or shoe C, draws in lubricant from the lead-in portion B, and, due to the rotation and the viscosity of the oil, layers of the fluid are drawn into the space.

The oil next to the journal rotates with it and that near the shoe *C* remains stationary, and, due to this condition, all the fluid contained in this area between the two surface layers is in a state of slip or shear. When these surfaces are relatively close to each other and converge in the direction of motion, the shear forces in the fluid are very great and a pressure is built up normal to the bearing surfaces supporting the journal *A* and its load, and prevents contact between journal and bearings.

The distribution of this pressure is shown by the curve *D*, the maximum being at *E*.

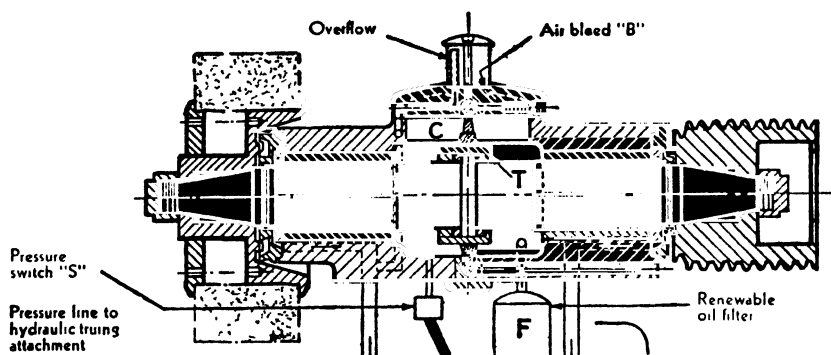
A section through a " Filmatic " bearing is shown in Fig 297, and a

Courtesy Cincinnati Milling Machines Ltd.

FIG. 298—GRINDING WHEEL SPINDLE SHOWING FILMATIC BEARING

layout of this bearing in the machine is indicated in Fig. 298, which shows a longitudinal section through the bearing and spindle.

In the bearing design the instability of the single oil-film structure is eliminated. Three or more self-adjusting shoes are used to produce independent converging oil films which develop high radial pressures, forcing the spindle into a central position. Since in this bearing an uninterrupted oil film is maintained between the bearing surfaces and the journal, its operation is virtually independent of the materials used for the journal and bearing. The maker's present standard construction in this respect employs a nickel-chrome steel spindle and steel bearing shoes with a high lead-bronze lining identical with that used in aero-engine bearings. Satisfactory results have also been obtained with other types of bronzes and cast iron and phenolic-resinoid bearings. The makers have applied this type of bearing to machines with horse-power ratings from 3 to 75, and spindle speeds from 1,000 to 10,000 r.p.m.

Another grinding-machine spindle bearing is the " Hydrauto " bearing of Messrs. Churchill Machine Tool Co. Ltd., Manchester. Two views are shown of this bearing in Fig. 299, which is a cross section through the Hydrauto bearing, and Fig. 300, which shows a section through a Hydrauto bearing wheel head.

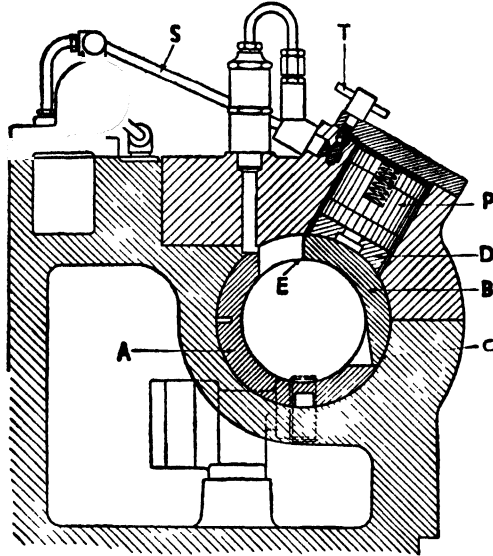
Earlier in this chapter the clearances were given for ordinary type bearings, which for general purposes are taken as 0·001 in. per inch of diameter. It may of course be less and in some instances might be as low as 0·0005 in. per inch of diameter with care. Even so, since many grinding operations are to-day finished to within 0·0001 in., it follows that a spindle 2 in. diameter with a possible float of 0·001 in. in the relatively thick film of oil is never in an exact position, and the spindle therefore floats uncertainly. The periphery of a grinding wheel mounted on such

Courtesy Churchill Machine Tool Co. Ltd.

FIG. 299—SECTION THROUGH HYDRAUTO BEARING

a spindle gives a slightly blurred outline, which can be distinguished by sound when the wheel is trued up by a diamond, and accurate grinding under these conditions is naturally very difficult. The Hydrauto bearing, however, which is self-adjusting, always maintains the minimum practical thickness of oil film.

The general principle is shown in Fig. 299, in which the fixed bearing *A* is rigidly mounted in the casting. The upper portion *B* rests on the spindle, and the heel portion *C* prevents *B* from rotating. A distance-piece *D* rests on *B*, and the piston *P* is lightly spring loaded. The chamber above the piston is filled with oil from the supply pipe *S*, and a one-way ball valve ensures that oil in the chamber over the piston cannot return. The bleeder valve plug *T* releases any air bubbles that may accumulate. In operation, as the spindle rotates the piston always tends to move downwards, but is prevented from rising by the non-return valve. The

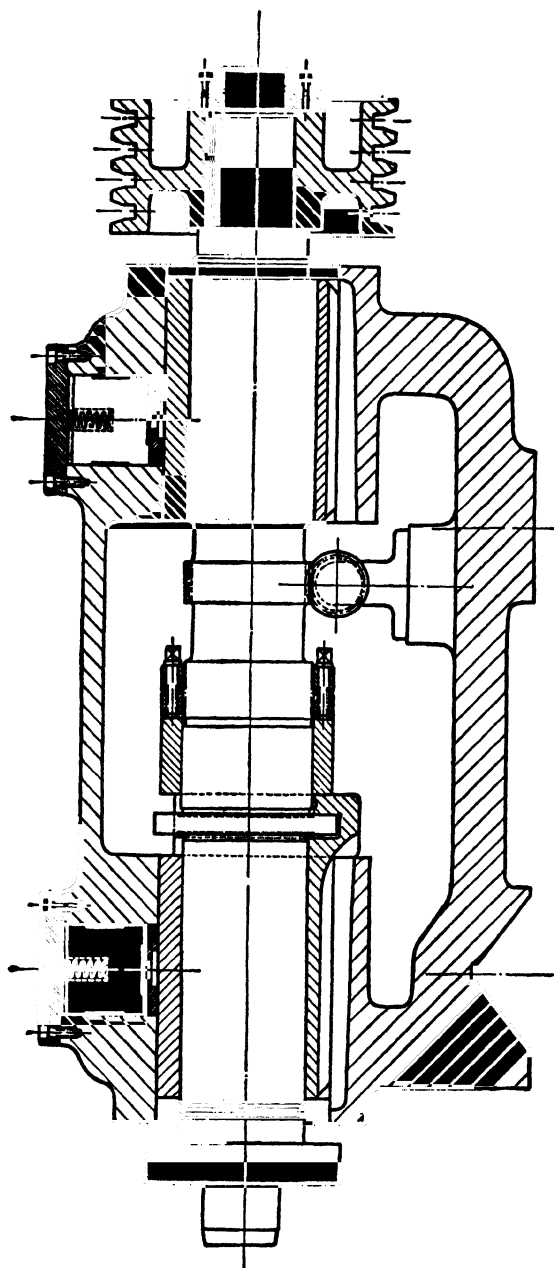



Fig. 300—Section through Hydrauto Bearing Wheel Head

oil film therefore is reduced to its practical minimum thickness, which is many times less than the clearance that has to be allowed for in bearings without the Hydrauto adjustment.

The sharp edge E helps to maintain the oil film at its minimum thickness.

The oil pressures developed in the bearings just referred to must, as is obvious, equal the bearing loads, otherwise the film would break down and allow metal to metal contact. In these bearings, as in all others, the loads at any point in the bearing can be calculated from a consideration

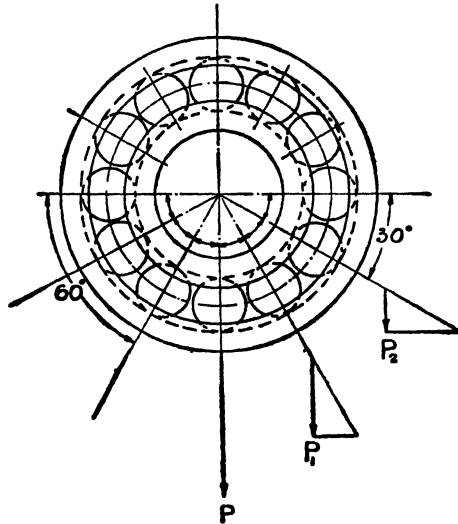



FIG. 301—BEARING LOADS

of the bearing load or bearing capacity. An example will show what is meant by this.

Refer to Fig. 301, which shows a ball or parallel roller bearing (it does not matter which for the purpose of determining the various loads P, P_1, or P_2, since these will be the same for a given value of P, which is determined from the load). For these given loads the stress on the ball or roller will vary according to the area of contact, and since the "line" contact of the parallel roller and taper roller is greater than the " point " contact of the ball, the corresponding stresses will vary accordingly.

Suppose the bearing load is 1,500 lb. acting vertically downwards, then this is distributed over five of the rolling or bearing elements, since the two shown on the horizontal centre line cannot take any portion of this load.

Thus, the values of P, P_1 and P_2 can be found in this manner :

$$1{,}500 = P + 2P_1 \cos 30° + 2P_2 \cos 60°$$
$$1{,}500 = P + 2P \cos^2 30° + 2P \cos^2 60°$$
$$1{,}500 = P(1 + 2 \cos^2 30° + 2 \cos^2 60°)$$

$$\therefore P = \frac{1500}{1 + 2\cos^{5/2} 30^\circ + 2\cos^{5/2} 60^\circ}$$

$$= \frac{1500}{1 + 2 \times 0{\cdot}866^{5/2} + 2 \times 0{\cdot}5^{5/2}} = \frac{1500}{1 + 2 \times 0{\cdot}6978 + 2 \times 0{\cdot}1768}$$

$$= \frac{1500}{1 + 1{\cdot}3956 + 0{\cdot}3536}$$

$$= \frac{1500}{2{\cdot}7492}$$

$$\therefore P = \mathbf{545{\cdot}6\ lb.}$$

Now $2P_1 \cos 30 = 2P \cos^{5/2} 30$ from above.

$$\therefore P_1 = \frac{P(2\cos^{5/2} 30)}{2\cos 30}$$

$$= \frac{P \times 2\cos^{5/2} 30^\circ}{2\cos 30^\circ}$$

$$= \frac{545{\cdot}6 \times 2 \times 0{\cdot}866^{5/2}}{2 \times 0{\cdot}866}$$

$$= \frac{545{\cdot}6 \times 2 \times 0{\cdot}6978}{1{\cdot}732}$$

$$= \frac{545{\cdot}6 \times 1{\cdot}3956}{1{\cdot}732}$$

$$\therefore P_1 = \mathbf{439{\cdot}5\ lb.}$$

Again:

$$2P_2 \cos 60 = 2P \cos^{5/2} 60^\circ$$

$$\therefore P_2 = \frac{2P\cos^{5/2} 60}{2\cos 60^\circ}$$

$$= \frac{2\cos^{5/2} 60 \times 545{\cdot}6}{2 \times 0{\cdot}5}$$

$$= \frac{545{\cdot}6 \times 0{\cdot}3536}{1}$$

$$\therefore P_2 = \mathbf{193{\cdot}5\ lb.}$$

Thus the highest loaded ball or roller in the bearing carries a load of 545·6 lb. and the stress on a diametral section $= \frac{P}{A} = \frac{545{\cdot}6}{A}$

If the ball or roller diameter is ½ in., then area $= \frac{\pi}{4} \times (\frac{1}{2})^2 = \frac{\pi}{16}$

$$\therefore f = \frac{545{\cdot}6 \times 16}{\pi}$$

$$\therefore f = \mathbf{2{,}777\ lb./in.^2}$$

The ball or roller is in contact with the inner race, and if an approximation be made, the radius R of the contact area can be found from:

$$R^3 = 1 \cdot 35 \frac{P}{E}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

Where R = Radius of area of contact of spherical bodies
R_1 = Radius of ball = 0·25 in.
R_2 = Radius of inner race = 0·75 in.
P = Load = 545·6 lb.
E = Young's Modulus = 30×10^6 lb./in.²

Substituting the values in the above expression, we get:

$$R^3 = \frac{1 \cdot 35 \times 545 \cdot 6}{30 \times 10^6}\left(\frac{1}{0 \cdot 25} + \frac{1}{0 \cdot 75}\right)$$

$$= \frac{1 \cdot 35 \times 545 \cdot 6 \times 5 \cdot 67}{30 \times 10^6}$$

$$R^3 = 0 \cdot 000102$$

$$R = \sqrt[3]{0 \cdot 000102}$$

$$\therefore R = \mathbf{0 \cdot 04672 \text{ in.}}$$

$$\text{Area of contact} = \pi R^2 = \pi \times 0 \cdot 04672^2$$

$$A = \mathbf{0 \cdot 006857 \text{ in.}^2}$$

Obviously the stress on this area will be much greater than across the diametral section and is equal to·

$$f = \frac{545 \cdot 6}{0 \cdot 006857}$$

$$f = \mathbf{79{,}580 \text{ lb./in.}^2}$$

If, instead of a ball, a roller of the same diameter and ¾ in. long were used, the contact area would be greater. For the sake of comparison let the roller be ½ in. diameter × ½ in. long, and by a similar method find the breadth of contact area B from:

$$\left(\frac{B}{4}\right)^2 = \frac{0 \cdot 58P}{E.L.}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\left(\frac{B}{4}\right)^2 = \frac{0 \cdot 58 \times 545 \cdot 6}{30 \times 10^6 \times 0 \cdot 5}\left(\frac{1}{0 \cdot 25} + \frac{1}{0 \cdot 75}\right)$$

$$B^2 = \frac{0 \cdot 58 \times 545 \cdot 6 \times 5 \cdot 67 \times 16}{15 \times 10^6}$$

$$= \frac{5 \cdot 8 \times 545 \cdot 6 \times 5 \cdot 67 \times 1 \cdot 6}{15{,}000{,}000}$$

$$B^2 = 0 \cdot 001914$$

$$B = \sqrt{0 \cdot 001914}$$

$$B = 0 \cdot 04374 \text{ in}$$

The contact area is $B \times L$

$$= 0{\cdot}04374 \times 0{\cdot}5$$
$$= \mathbf{0{\cdot}02187\ sq.\ in.}$$
$$\text{Stress } f = \frac{545{\cdot}6}{0{\cdot}02187}$$
$$f = \mathbf{24{,}950\ lb./in.^2}$$

The question of bearings for machine-tool spindles has been associated with " preloading," a feature which enables a certain amount of preload to be applied to the bearing at its initial assembly. In the case of a taper roller bearing, this is easily accomplished by adjusting the bearings with

(A) Press or shrink fit calculations are based on radial deformation of a cylinder subjected to uniformly distributed internal and external pressures.
(B) Cases of shrink or press fit are considered as two cylinders as shown.

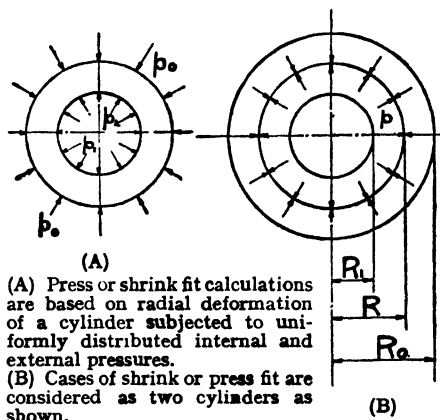



FIG. 302—PRESS FITS

a slight binding effect. The temperature rise limits the amount of preload which can be applied.

In the case of ball and parallel roller bearings, preload can be applied by arranging the interference of either or both the shaft in the inner race and the outer race in the bearing housing to eliminate all radial clearance or give a slight binding effect. This, then, definitely locates the spindle or part carried by the bearings, and the only inaccuracies are those of the bearing itself, which can be of the order of 0·0001–0·0003 in. maximum ; but by careful assembly and selective mounting, so that bearing inaccuracies cancel each other out, very accurate assemblies can be obtained.

This question of the interference of bearing parts with their mating members leads us to the question of shrink or interference fits and their relation to bearing clearances. The general condition is represented in Fig. 302, in which A indicates the radial deforming forces on a cylinder due to uniform internal and external pressures ; B shows how the problems may be studied by considering the bearings as two cylinders.

When a bearing or bush is pressed or shrunk into position, the inside

and outside diameters are always affected, the degree to which they are altered depending upon the type of material and the amount of shrink fit or interference involved. These changes in the dimensions may have an important effect on the accuracy and precision of the job, and will affect cost and production in so far as the variation in size may affect the accuracy and finish of the components themselves. Obviously it is no use machining a bore to a close limit if it is to be affected by a press fit and the amount of variation is not known. Moreover, a predetermined amount of clearance cannot be obtained unless this factor is calculable. It is true that tests on actual assemblies will give information on this point, but it is a costly process, wasteful in time and not generally satisfactory. However, variations in size due to the deformations resulting from press fits can be calculated and the parts concerned can be made finish machined to sizes which will give the required running clearance when assembled.

When approaching the problem, the following assumptions must first be made :

1. That the materials concerned are homogeneous.
2. That the section is uniform throughout (the slight variation in the parts concerned will not materially affect the problem)

In the problems that follow, the symbols given below are used .

R_1 = Inner radius.
R_o = Outer radius.
R = Contact radius.
p_1 = Inner pressure.
p_o = Outer pressure.
m = Poisson's ratio.
D_R = Radial deformation at radius R.
E_o = Modulus of elasticity (Young's Modulus) for outer cylinder
E_1 = Modulus of elasticity for inner cylinder.
m_o = Poisson's ratio for outer cylinder material.
m_1 = Poisson's ratio for inner cylinder material.
f = Press or shrink fit between inner and outer cylinder.
D_a = Increase in inner radius of outer cylinder.
D_b = Decrease in outer radius of inner cylinder.
D_c = Decrease in inner radius of inner cylinder.
D_d = Increase in outer radius of outer cylinder.
p = Contact pressure between cylinders.

The value of p can be obtained from a consideration of the fact that the sum of the magnitudes of the deformations of both cylinders at the radius R (contact radius) caused by p must be equal to f.

This condition can be expressed as an equation thus :

$$D_a - D_b = f \qquad . \quad (1)$$

and since the general expression for radial deformation of a cylinder acted upon by uniformly distributed internal and external pressures p_1 and p_o respectively is given by:

$$D_R = \frac{1-m}{E} \times \frac{R_1^2 p_1 - R_o^2 p_o}{R_o^2 - R_1^2} \times R + \frac{1+m}{E} \times \frac{R_1^2 R_o^2 (p_1 - p_o)}{(R_o^2 - R_1^2) R} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

We can find equations for D_a and D_b from equation (2) as follows:

$$D_a = \frac{R_o p}{E_o}\left[\frac{R_o^2 + R^2}{R_o^2 - R^2} + m_o\right] \quad . \quad . \quad . \quad (3)$$

$$D_b = \frac{-Rp}{E_1}\left[\frac{R_1^2 + R^2}{R^2 - R_1^2} - m_1\right] \quad . \quad . \quad . \quad (4)$$

Now by substituting equations (3) and (4) in equation (1):

$$f = \frac{Rp}{E_o}\left[\frac{R^2 + R_o^2}{R_o^2 - R^2} + m_o\right] + \frac{Rp}{E_1}\left[\frac{R_1^2 + R^2}{R^2 - R_1^2} - m_1\right]$$

which, by solving for p, gives—

$$p = \frac{f}{\frac{R}{E_o}\left[\frac{1+\left(\frac{R}{R_o}\right)^2}{1-\left(\frac{R}{R_o}\right)^2} + m_o\right] + \frac{R}{E_1}\left[\frac{1+\left(\frac{R_1}{R}\right)^2}{1-\left(\frac{R_1}{R}\right)^2} - m_1\right]} \quad . \quad (5)$$

Using this value for p, we can find expressions for D_c and D_d.

$$D_c = \frac{-2R_1}{E_1\left[1-\left(\frac{R_1}{R}\right)^2\right]} \times p \quad . \quad . \quad . \quad (6)$$

$$D_d = \frac{2R\left(\frac{R}{R_o}\right)}{E_o\left[1-\left(\frac{R}{R_o}\right)^2\right]} \times p \quad . \quad . \quad . \quad (7)$$

Now these equations can be simplified when the cylinders are of the same materials, as in ball and roller bearings, in which case $E_1 = E_o$ and $m_1 = m_o$.

Combining equations (5) and (6):

$$D_c = \frac{-\left(\frac{R_1}{R}\right)\left[1-\left(\frac{R}{R_o}\right)^2\right]}{\left[1-\left(\frac{R_1}{R_o}\right)^2\right]} \times f \quad . \quad . \quad (8)$$

Now combining equations (5) and (7), and again taking note of the fact that $E_o = E_1$ and $m_o = m_1$, we get:

$$D_d = \frac{\frac{R}{R_o}\left[1 - \left(\frac{R_1}{R}\right)^2\right]}{\left[1 - \left(\frac{R_1}{R_o}\right)^2\right]} \times f \quad . \quad . \quad . \quad (9)$$

These equations can be further simplified for cases where the materials are the same and a bush is pressed on a shaft of the same material. In this case equation (9) becomes:

$$D_d = \frac{R}{R_o} \times f = \frac{fR}{R_o} \quad . \quad . \quad . \quad . \quad (10)$$

The foregoing equations, that is Nos. (5)–(10), will cover all the problems involving the solution of radial deformations, i.e. alterations in size ; even though they refer to purely cylindrical parts such as bushes, they can be used to find the deformations of stepped bushes or variable parts by taking the mean diameter and using this mean value in the appropriate equation.

Example.—A gunmetal bush, 1½ in. bore, 2·002 in. outside diameter, is pressed into a cast-iron housing 2 in. bore and 2½ in. outside diameter. If Young's Modulus is 12,000,000 lb./in.² for cast iron and 10,000,000 lb./in.² for gunmetal, and Poisson's ratio for cast iron = 0·27 and for gunmetal 0·33, find the decrease in the bore of the bush.

It will be found advantageous to put down all the items involved as follows:

$E_o = 12 \times 10^6$

$E_1 = 10 \times 10^6$

$m_o = 0{\cdot}27$

$m_1 = 0{\cdot}33$

$\frac{R_1}{R} = \frac{0{\cdot}75}{1{\cdot}00} = 0{\cdot}75$

$\frac{R}{R_o} = \frac{1{\cdot}00}{1{\cdot}25} = 0{\cdot}8$

$f = \frac{2{\cdot}002 - 2}{2} = 0{\cdot}001$ in.

$R_1 = 0{\cdot}75$

$R_o = 1{\cdot}25$

$R = 1{\cdot}001$

$\left(\frac{R_1}{R}\right)^2 = 0{\cdot}562$

$\left(\frac{R}{R_o}\right)^2 = 0{\cdot}64$

Using equation (5)

$$p = \frac{f}{\frac{R}{E_o}\left[\frac{1 + \left(\frac{R}{R_o}\right)^2}{1 - \left(\frac{R}{R_o}\right)^2} + m_o\right] + \frac{R}{E_1}\left[\frac{1 + \left(\frac{R_1}{R}\right)^2}{1 - \left(\frac{R_1}{R}\right)^2} - m_1\right]}$$

$$p = \frac{0{\cdot}001}{\frac{1{\cdot}001}{12 \times 10^6}\left[\frac{1 + 0{\cdot}64}{1 - 0{\cdot}64} + 0{\cdot}27\right] + \frac{1{\cdot}001}{10 \times 10^6}\left[\frac{1 + 0{\cdot}562}{1 - 0{\cdot}562} - 0{\cdot}33\right]}$$

$$\therefore p = \mathbf{1,840\ lb./in.^2}$$

Now use equation (6):

$$D_c = \frac{-2R_1}{E_1\left[1 - \left(\frac{R_1}{R}\right)^2\right]} \times p$$

$$= \frac{-2 \times 0{\cdot}75}{10 \times 10^6\ [1 - 0{\cdot}562]} \times 1840$$

$$D_c = \mathbf{0{\cdot}00063\ in.}$$

Thus the decrease in the inside diameter will be twice this amount:

$$= 2 \times 0{\cdot}00063$$
$$= 0{\cdot}00126$$

and the bore will be **1·49874 in. diameter.**

If now the same bush were to be pressed on to a solid shaft say of steel with a modulus of elasticity $E = 30{,}000{,}000$ lb./in.^{2} and measuring 1·502 in., that is, 2 thousandths bigger than the bore of the bush, we can find the increase of the outside diameter.

Let bush be 1·500 in. bore and 2·000 in. outside diameter. As before, put down all the factors involved:

$E_1 = 30 \times 10^6$ $\quad f = 0{\cdot}001$ in. $\quad \frac{R_1}{R} = 0 \quad \left(\frac{R_1}{R}\right)^2 = 0$

$E_o = 10 \times 10^6$ $\quad R_1 = 0$

$m_1 = 0{\cdot}30$ $\quad R_o = 1$ $\quad \frac{R}{R_o} = 0{\cdot}75 \quad \left(\frac{R}{R_o}\right)^2 = (0{\cdot}75)^2 = 0{\cdot}562$

$m_o = 0{\cdot}33$ $\quad R = 0{\cdot}75$

As before, from equation (5) find p:

$$p = \frac{0{\cdot}001}{\frac{0{\cdot}75}{30 \times 10^6}\left[\frac{1 + 0{\cdot}562}{1 - 0{\cdot}562} + 0{\cdot}33\right] + \frac{0{\cdot}75}{10 \times 10^6}\left[\frac{1+0}{1-0} - 0{\cdot}30\right]}$$

$$p = \mathbf{3{,}240\ lb./in.^2}$$

Now, using equation (7):

$$D_d = \frac{2R\left(\frac{R}{R_o}\right)}{E_o\left[1 - \left(\frac{R}{R_o}\right)^2\right]} \times p$$

$$= \frac{2 \times 0{\cdot}75\ (0{\cdot}75)}{10 \times 10^6\ [1 - 0{\cdot}562]} \times 3240$$

$$D_d = 0{\cdot}000825$$

Thus, the increase in the outside diameter will be twice this:

$$= 2 \times 0{\cdot}000825$$
$$= \mathbf{0{\cdot}001650\ in.}$$

and the final diameter will be 2·000 + 0·00165. Outside diameter of bush will be 2·00165 in.

From the foregoing it will be seen that there are many problems which can be solved by this method. For example, a definite fit can be obtained by arranging the variables to obtain it, and conversely the amount of fit required for a given pressure between the contact surfaces can be calculated. This latter can be useful in cases where the holding power of a bush or bearing race on its seating relies entirely on the mounting pressure, and as already indicated, a reliable guide or verification of the fit decided upon can be given by transposing the terms of equation (5), which contains both p and f, the pressure and fit. From this we get:

$$\text{fit}, f = p\left[\frac{R}{E_o}\left\{\frac{1+\left(\frac{R}{R_o}\right)^2}{1-\left(\frac{R}{R_o}\right)^2} + m_o\right\} + \frac{R}{E_1}\left\{\frac{1+\left(\frac{R_1}{R}\right)^2}{1-\left(\frac{R_1}{R}\right)^2} - m_1\right\}\right]$$

Example.—What fit or radial deformation would have to be obtained in a journal bearing 4 in. bore and 5 in. outside diameter when mounted on a solid shaft of the same material which has a modulus of elasticity $E = 30{,}000{,}000$ lb./in.^{2} and Poisson's ratio 0·3 if the pressure between the two parts has to be 10,000 lb./in.^{2}?

$$R_1 = 0 \quad R = 2 \quad R_o = 2\tfrac{1}{2} \quad \frac{R}{R_o} = 0{\cdot}8\,; \left(\frac{R}{R_o}\right)^2 = 0{\cdot}64; \ \frac{R_1}{R} = 0\,; \left(\frac{R_1}{R}\right)^2 = 0$$

Using the formula just found:

$$f = p\left[\frac{R}{E}\left\{\frac{1+\left(\frac{R}{R_o}\right)^2}{1-\left(\frac{R}{R_o}\right)^2} + m\right\} + \frac{R}{E}\left\{\frac{1+\left(\frac{R_1}{R}\right)^2}{1-\left(\frac{R_1}{R}\right)^2} - m\right\}\right]$$

$$= 10{,}000\left[\frac{2}{30\times 10^6}\left\{\frac{1+0{\cdot}64}{1-0{\cdot}64} + 0{\cdot}3\right\} + \frac{2}{30\times 10^6}\left\{\frac{1+0}{1-0} - 0{\cdot}3\right\}\right]$$

$$= 10{,}000\left[\frac{2}{30\times 10^6}\left\{\frac{1{\cdot}64}{0{\cdot}36} + 0{\cdot}3\right\} + \frac{2}{30\times 10^6}\left\{1 - 0{\cdot}3\right\}\right]$$

$$= 10{,}000\left[\frac{2}{30\times 10^6}\left\{4{\cdot}555 + 0{\cdot}3\right\} + \frac{2}{30\times 10^6}\left\{0{\cdot}7\right\}\right]$$

$$= 10{,}000\left[\frac{2}{30\times 10^6}(4{\cdot}855) + \frac{1{\cdot}4}{30\times 10^6}\right]$$

$$= 10{,}000\left(\frac{9{\cdot}71 + 1{\cdot}4}{30\times 10^6}\right)$$

$$= \frac{10{,}000 \times 11{\cdot}11}{30{,}000{,}000}$$

$$= \frac{111{,}100{\cdot}0}{30{,}000{,}000}$$

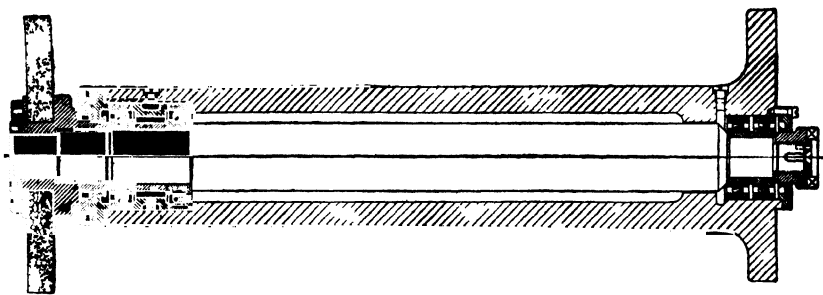
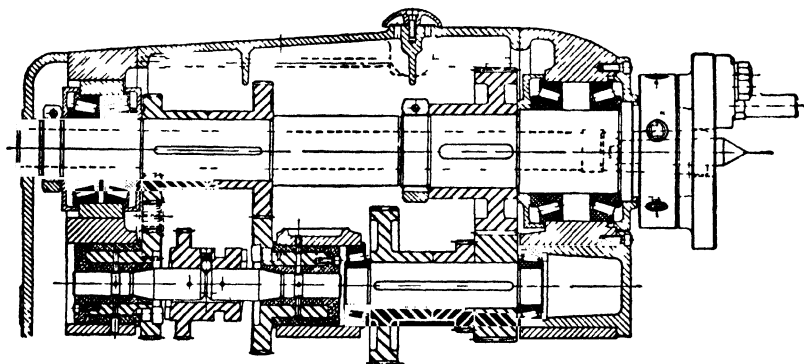
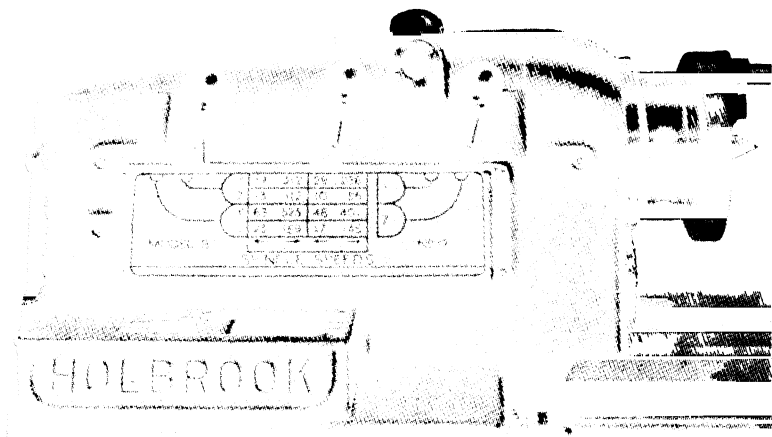
$\therefore f =$ **0·003703 in.**

Courtesy Churchill Machine Tool Co Ltd

FIG 303—INTERNAL GRINDING SPINDLE

HOLBROOK

Above view shows arrangement of Pre-loading Bearings and Synchromesh Reverse Clutch.

Courtesy Holbrook Machine Tool Co Ltd

FIG. 304—SECTION THROUGH LATHE HEADSTOCK SHOWING SPINDLE BEARINGS

i.e. the radial interference must be 0·003703 and the outside diameter of the shaft will be :

$$4 + 2 \times 0{\cdot}003703 = 4 + 0{\cdot}007406$$
$$= \mathbf{4{\cdot}0074\ in.}$$

Many similar problems will doubtless suggest themselves, and they may be dealt with on the lines indicated in the foregoing examples.

Spindles

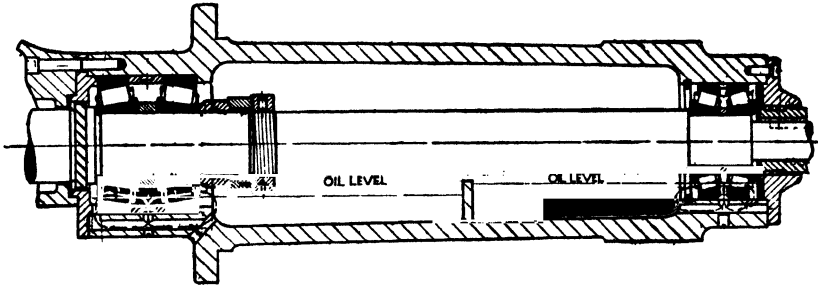
In Chapters V and VI some spindles have been indicated, and the spindles using Filmatic, Hydrauto and ball bearings have been mentioned in this

Courtesy British Timken Ltd

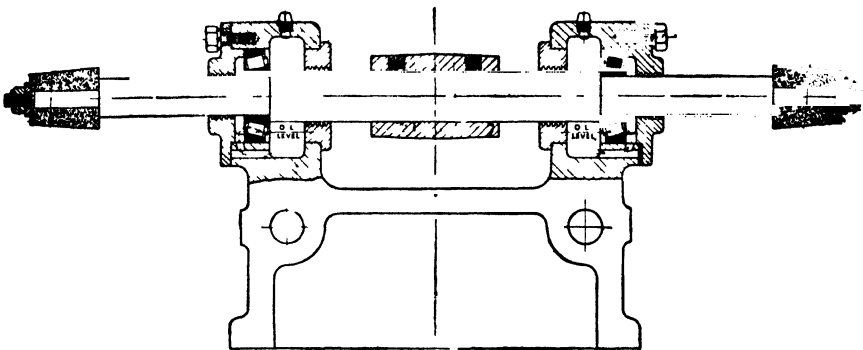
FIG. 305—GRINDING SPINDLE MOUNTED ON TAPER ROLLER BEARINGS

Courtesy British Timken Ltd

FIG 306—POLISHING OR GRINDING SPINDLE

chapter. There now remains the ball and taper roller bearing spindle.

In Fig. 303 is shown a detachable tube-type internal grinding spindle as used on Churchill Internal Grinding Machines, using ball bearings for carrying the spindle and taking the loads.

The mounting is simple and straightforward, and does not call for special comment.

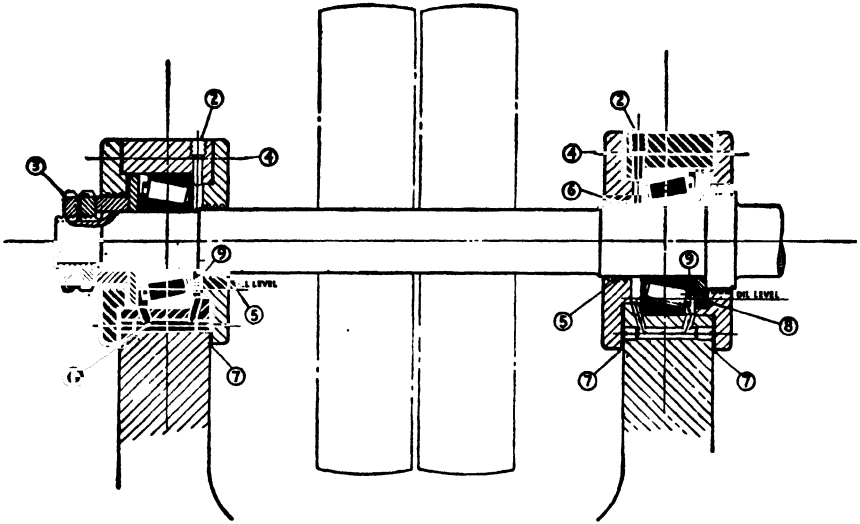
The Timken equipped headstock shown in Chapter VI, Fig. 145, is

Courtesy British Timken Ltd.

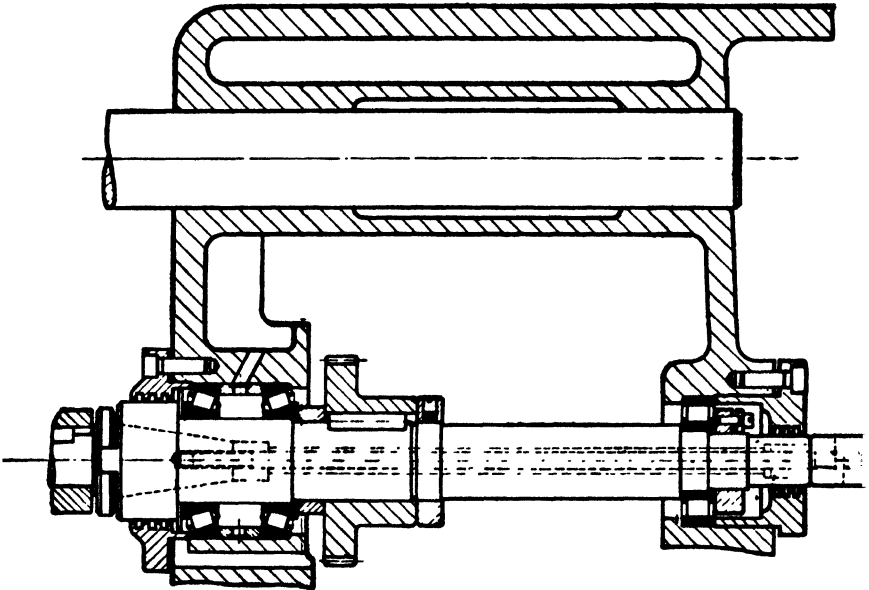
FIG. 307—SMALL MILLING SPINDLE

Courtesy British Timken Ltd.

FIG. 308—MILLING MACHINE SPINDLE

further illustrated in Fig. 304, which shows a Precision Tool-room Lathe. Here it will be noted that the bearings at the spindle nose are of the flanged-cup type, the cups or outer races being press fitted into the body of the headstock casting. At the rear end of the spindle, similar bearings are carried in a sleeve which is free to float endwise in the main housing; this allows the expansion of the spindle to be taken up without affecting the bearings or their initial adjustment.

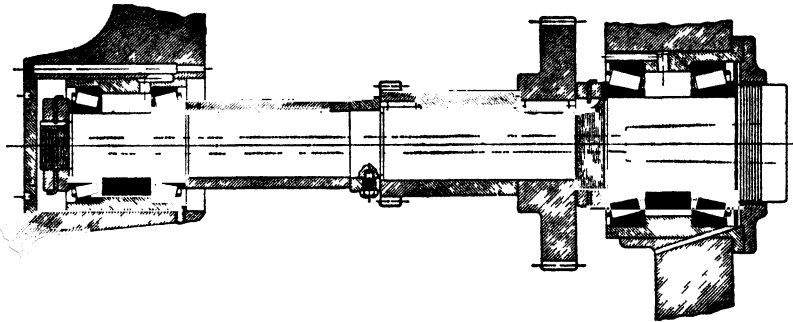
The application of the tapered roller bearings to a grinding spindle is shown in Fig. 305, and this design is not unlike that shown in Figs. 96 and 98. The bearings at the left-hand end of the spindle are provided with cup and cone spacers, and these are machined to give correct bearing clearances. At the other end a double cup bearing, i.e. a double outer

Courtesy British Timken Ltd

FIG. 309—HEAVY DUTY MILLING MACHINE SPINDLE

race, is fitted, and here, too, a cone spacer is fitted. Subsequent bearing adjustment can be effected by the addition or subtraction of shims of known thickness between the cones and cone spacers.

A similar type of layout for a grinding and buffing wheel spindle is shown in Fig. 306. In this instance only single bearings are used, and it should be noted that this arrangement is not suitable for long spindles, or in fact for any spindle where variation in spindle length due to changes of temperature are likely to occur, as this will affect the bearing clearance.

The same bearing layout is shown in Fig. 307, in which two single bearings are used for a small milling-machine spindle.

A further milling-machine spindle bearing layout is shown in Fig. 308. In this case there are two bearings at the spindle nose end where the arbor joins the spindle. Any variations in the spindle due to temperature rise when the machine is running can be accounted for by allowing the spindle to float in a parallel roller bearing at the rear of the spindle. In the case shown here, the spindle bearing inner race and the rollers can slide in the outer race of the rear bearing, taking up any allowance required by the rise in temperature due to continued working conditions.

A typical heavy duty milling machine spindle is shown in Fig. 309.

In capstan and automatic lathe work it is necessary at times to compute the number of pieces which can be obtained from a bar of given length. With this figure known, it is an easy step to arrive at the number of bars of material which will be required for a given order. The factors governing the number of pieces of given length from standard bars of 10-, 12-, 14-ft. length are the lengths of workpiece, width of parting tool, and the amount left in the chuck or collet when the last piece is being machined. This amount, known as the bar-end allowance, varies with the length of the component. For work up to and including 1½ in. long the bar-end allowance can be taken as 1·5 times component length; for pieces exceeding 1½ in. long, the allowance is usually 3 in.

Let l = Component length.
L = Bar length.
W = Width of parting tool.
N = Number of pieces.

$$\text{Then } N = \frac{L - 1{\cdot}5l}{l + W} \text{ for work up to } 1\tfrac{1}{2} \text{ in. long.}$$

$$N = \frac{L - 3}{l + W} \text{ for work over } 1\tfrac{1}{2} \text{ in. long.}$$

The expressions are easily applied and give the number of pieces which should be obtained working at 100 per cent.; that is, not allowing for any scrap pieces. If 6 per cent. scrap is allowed, then the number will be 0·94 of the quantity given by the expression for N.

The production engineer will have many new problems to face resulting from the new materials necessitated by the high temperatures encountered in gas turbines and jet-propulsion units.

The materials for certain parts of these units must be capable of withstanding high temperatures, and steels and alloys capable of working at high temperatures usually are very difficult to machine. For some of these materials tungsten carbide is suitable, but there are others which require a special high-speed steel. The ordinary 18–20 per cent. tungsten high-speed steel has been satisfactory for these new steels, but in some instances a 22 per cent. tungsten steel is necessary, and no doubt higher percentages of tungsten will be tried as and when occasion demands.

The high-temperature properties of these heat-resisting alloys, such as Nimonic Alloys, prevent the " plasticisation " of the chip, with the result that high-speed cutting with negative rake tools is impossible, hence the use of high-speed steel tools already mentioned. The cutting speed for these alloys is limited to a maximum of 35 ft. per minute, the cutting tools used having a positive rake angle.

A suitable tool steel is one containing 18 per cent. tungsten and 5 per cent. cobalt ; also 10 per cent. cobalt is used in some cases where the combined properties of toughness and red hardness are required.

The notes just given refer to milling. For turning, carbide tools can be used providing that positive rakes of 5° top and 15° side are used for roughing cuts and 5° top with 5° side rake for finishing cuts. With these angles tools can successfully operate on heat-resisting steels at cutting speeds between 100 and 150 ft. per minute.

For profiling and screwcutting high-speed-steel cutting tools must be used.

There is no difficulty to be encountered when grinding, although it is preferable to use an alundum (aluminium oxide) wheel.

It is hoped that the notes given will indicate the trend in modern production methods and serve to stimulate the reader's interest in recent developments. See Henry Wiggin & Co. Ltd., publication, *Notes on Machining the Nimonic Alloys.*

Exercises on Chapter X

1. Describe the trend in the design of modern machine tools, giving details of spindle speeds and finish of work.

2. Contrast plain bearings and antifriction bearings, including a sketch of the lubrication of the plain bearing.

3. A plain bearing, 3 in. diameter, 6 in. long, supports a load of 7,250 lb. and revolves at 500 r.p.m. Calculate the coefficient of friction μ for the bearing and the horse-power lost to friction in the bearing.

4. Describe one of the following bearings : (*a*) Filmatic ; (*b*) Hydrauto ; (*c*) Timken ; (*d*) Schiele, illustrating the points you mention by reference to a suitable sketch.

5. Calculate the heat equivalent of the friction horse-power, and hence determine the amount of oil of specific heat 0·55 and 7·8 lb. per gallon which would be required per hour to ensure that the temperature rise within the bearing chamber did not exceed 5° F. for conditions in Question 3.

6. On what does the holding power between two surfaces, as in the case of a bearing bush in a housing, depend ? State the principle underlying the consideration of problems involving bushes and similar parts.

7. A bronze bush, $1\frac{1}{2}$ in. bore and 2·002 in. outside diameter, is pressed into a housing, 2 in. bore and 2·5 in. outside diameter, made of the same material. Find the decrease in the inside diameter of the bush.

8. Find the increase in the outside diameter of a bush $1\frac{1}{2}$ in. bore by 2 in. outside diameter when it is pressed on a hollow shaft of the same material. Shaft is 1·502 in. outside diameter and 1 in. bore.

9. If the shaft in Question 8 had been solid, what would the increase in outside diameter of the bush be ?

10. What would be the diameter of a shaft if it has to be pressed into a wheel with a bore of 2 in. Take the wheel boss as $4\frac{3}{4}$ in., and ignore the effect of spokes and rim. The fit is to be such that the holding pressure between wheel and shaft is to be 8,000 lb./in.^{2}.
Take E for wheel $= 30 \times 10^6$ lb./in.^{2}, and for shaft 33×10^6; m for wheel $= 0{\cdot}3$ and for shaft 0·33.

For those who wish to obtain a wider knowledge of the various machines and processes dealt with in this book, the following list may be of assistance :

LATHES

Automatic Screw Machine. Browne and Sharp, Providence, R.I. Buck & Hickman Ltd., London

Cam Design in Autos. B.S.A. Tools Ltd. 10*s*. 6*d*.
Capstan and Turret Lathes.
Turret Lathe Work. Alfred Herbert Ltd. 7*s*. 6*d*.
Modern Tooling Methods for Turret Lathes. Lange.
Capstan and Turret Lathes (*Catalogue*). H. Ward & Co. Ltd.
Turret Lathe Operator's Manual. Warner & Swasey Ltd.
Multi-spindle Automatics. A. C. Wickman Ltd., Coventry.
The Mechanisms of Machine Tools. T. R. Shaw. Frowde & Hodder & Stoughton Ltd., London.
Machine Tool Work. Turner and Owen. McGraw Hill Pub. Co. Ltd.

Cutting Tools

Cutting Tool Practice. H. C. Town. Paul Elek Ltd., London.
Cutting Tools for Metal Machining. M. Kurrein and F. C. Lea. Charles Griffin & Co. Ltd., London.
Wimet Standard Tools Manual. A. C. Wickman Ltd., Coventry.

Milling

Practical Treatise on Milling. Browne and Sharpe.
Universal Dividing Head. Cincinatti Milling Machines Ltd., Tyburn, Birmingham.
High-speed Milling Machines. Cincinatti Milling Machines Ltd., Tyburn, Birmingham.

Grinding

Centreless Grinding Machines. Cincinatti Milling Machines Ltd., Tyburn, Birmingham.
Centreless Grinding Data. Churchill Machine Tools Ltd., Broadheath, Manchester.
Grinding Practice. Colvin and Stanley. McGraw Hill Pub. Co. Ltd.
Grinding Data. Churchill Machine Tools Ltd., Broadheath, Manchester.
A Handbook of Grinding. Carborundum Co. Ltd., Trafford Park, Manchester.
Tool and Cutter Grinding. Cincinatti Milling Machines Ltd., Tyburn, Birmingham.

Gears and Gear Cutting

Gears. H. E. Merritt. Sir Isaac Pitman, London.
Maxicut Gear Cutting Machines. Drummond Bros. Ltd., Guildford.
Sunderland Gear Planers. T. Parkinson & Son, Shipley, Yorkshire.

The Yellow Back Series and other works of the Machinery Publishing Co. Ltd. also cover many phases of the work, and most firms have technical literature available which deals with their product

The Production Engineering Research Association (P.E.R.A.) of Great Britain, Melton Mowbray, Leicestershire, also publish information, and the forerunner of this body, The Research Department of the Institution of Production Engineers, have some books available. The following are noteworthy:

Machine Tool Research and Development, by Dr. D. F. Galloway. 10*s*. 6*d*. I.P.E. Research Dept., 10, Chesterfield Street, London, W.1.

Surface Finish, by Dr. Geo. Schlesinger. 15*s*. 6*d*. The Institution of Production Engineers, 10, Chesterfield Street, London, W.1.

Test Charts for Machine Tools. The Institution of Production Engineers, 10, Chesterfield Street, London, W.1.

Lastly, there are the publications of the British Standards Institution, 2, Park Street, London, W.1, which are too numerous to list here. However, one of these B.S.I. publications is *Workshop Practice*, 10*s*. 6*d*., which will be found to contain useful data on many of the sections of the work dealt with in this book.

CUTTING-SPEED CONVERSION TABLE

Feet per minute (columns) — *Revolutions per minute* (body)

Dia in	10	12	14	16	18	20	25	30	35	40	45	50	60	70	80	90	100	110	120	150	200	250	Dia mm
1/2	76	92	107	122	137	153	191	228	267	306	344	382	458	535	611	688	764	840	916	1146	1528	1910	12
5/8	61	73	86	98	110	122	153	183	214	244	275	306	367	428	489	550	611	672	733	918	1224	1530	15
3/4	51	61	71	81	92	102	127	153	178	204	229	254	306	357	407	458	509	560	611	764	1016	1270	19
7/8	44	52	61	70	79	87	109	131	153	175	196	218	262	306	349	393	436	480	523	645	876	1090	22
1	38	46	53	61	69	76	95	114	134	153	172	191	229	267	306	344	382	420	458	573	764	955	25
1¼	31	37	43	49	55	61	76	91	107	122	138	153	183	214	244	275	305	336	366	459	612	765	31
1½	25	30	36	41	46	51	64	76	89	102	114	127	153	178	204	229	254	280	305	381	508	635	38
1¾	22	26	30	35	39	44	55	65	76	87	98	109	131	153	175	196	218	240	262	327	436	545	44
2	19	23	27	30	34	38	48	57	67	76	86	95	114	133	153	172	191	210	229	287	382	475	50
2¼	17	20	24	27	30	34	42	51	59	68	76	85	102	119	136	153	170	187	204	255	340	425	57
2½	15.3	18.3	21	24	27	31	38	46	53	61	69	76	92	107	122	137	153	168	183	230	306	380	63
2¾	13.8	16.6	19.4	22	25	28	35	42	49	55	62	69	83	97	111	125	139	152	166	209	278	345	69
3	12.7	15.2	17.8	20	23	25	32	38	44	51	57	64	76	89	102	115	127	140	153	191	254	320	76
3¼	11.7	14	16.4	18.8	21	23	29	35	41	47	53	59	70	82	94	106	117	129	141	176	234	295	82
3½	10.9	13	15.3	17.4	19.6	22	27	33	38	44	49	54	65	76	87	98	109	120	131	164	218	270	88
3¾	10.2	12.2	14.2	16.3	18.3	20.3	25	30	36	41	46	51	61	71	81	92	102	112	122	153	205	255	95
4	9.5	11.4	13.4	15.2	17.2	19	24	29	33	38	43	48	57	67	76	86	95	105	114	143	191	240	101
4½	8.5	10.2	11.9	13.6	15.3	17	21	25	30	34	38	42	51	59	68	76	85	93	102	127	170	210	114
5	7.6	9.2	10.7	12.2	13.7	15.3	19	23	27	30	34	38	46	53	61	69	76	84	92	115	153	190	127
5½	6.9	8.3	9.7	11	12.5	13.9	17.4	20.8	24	28	31	35	42	49	55	62	69	76	83	104	139	175	139
6	6.4	7.6	8.9	10.2	11.5	12.7	15.9	19	22	25	28	32	38	44	51	57	64	70	76	95.4	127	160	152
7	5.5	6.5	7.6	8.7	9.8	10.9	13.6	16.4	19	22	25	27	33	38	44	49	54	60	65	82	109	135	177
8	4.8	5.7	6.7	7.6	8.6	9.5	11.9	14.3	16.7	19	21	24	29	33	38	43	48	52	57	72	96	120	203
9	4.3	5.1	5.9	6.8	7.6	8.5	10.6	12.7	14.9	17	19	21.2	25	30	34	38	42	47	51	64	85	106	228

Brinell Hardness Numbers

D = Ball diameter = 10 mm. P = Pressure = 3,000 Kg.
S = Diameter of Ball Impression in mm.

$$\text{Brinell No.} = \frac{P}{0{\cdot}7854S^2} = \frac{P}{\pi D\left(\frac{D}{2} - \sqrt{\frac{D^2 - S^2}{4}}\right)}$$

Diameter of Ball Impression S mm	*Brinell Hardness Number*	*Approx Tonnage*	*Diameter of Ball Impression S mm*	*Brinell Hardness Number*	*Approx. Tonnage*
2·0	946	206	4·5	179	39·5
2·1	857	187	4·6	170	38·5
2·2	782	171	4·7	163	37·5
2·3	713	155	4·8	156	36
2·4	652	142	4·9	149	34
2·5	600	131	5·0	143	33
2·6	555	121	5·1	137	31
2·7	512	112	5·2	131	30
2·8	477	105	5·3	126	29
2·9	444	97	5·4	121	28
3·0	418	91	5·5	116	26
3·1	387	84	5·6	112	25
3·2	364	79	5·7	107	24
3·3	340	74	5·8	103	23
3·4	321	70	5·9	99	22·7
3·5	302	66	6·0	95	22
3·6	286	62	6·1	92	21
3·7	269	59	6·2	89	20·5
3·8	255	55	6·3	86	19·7
3·9	241	52	6·4	82	19
4·0	228	50	6·5	80	18·5
4·1	217	47	6·6	77	17·7
4·2	207	45	6·7	74	17
4·3	196	43	6·8	71·5	16·5
4·4	187	41	6·9	69	16

The ultimate tensile strength, U.T.S., of carbon steels, mild and medium, is given approximately by U.T.S. = Brinell No. × 0·22

Decimal Equivalents of Fractions

Fraction	*Decimal Equivalent*	*Fraction*	*Decimal Equivalent*	*Fraction*	*Decimal Equivalent*
$\frac{1}{64}$	0·015625	$\frac{11}{32}$	0·34375	$\frac{43}{64}$	0·671875
$\frac{1}{32}$	0·03125	$\frac{23}{64}$	0·359375	$\frac{11}{16}$	0·6875
$\frac{3}{64}$	0·046875	$\frac{3}{8}$	0·375	$\frac{45}{64}$	0·703125
$\frac{1}{16}$	0·0625	$\frac{25}{64}$	0·390625	$\frac{23}{32}$	0·71875
$\frac{5}{64}$	0·078125	$\frac{13}{32}$	0·40625	$\frac{47}{64}$	0·734375
$\frac{3}{32}$	0·09375	$\frac{27}{64}$	0·421875	$\frac{3}{4}$	0·750
$\frac{7}{64}$	0·109375	$\frac{7}{16}$	0·4375	$\frac{49}{64}$	0·765625
$\frac{1}{8}$	0·125	$\frac{29}{64}$	0·453125	$\frac{25}{32}$	0·78125
$\frac{9}{64}$	0·140625	$\frac{15}{32}$	0·46875	$\frac{51}{64}$	0·796875
$\frac{5}{32}$	0·15625	$\frac{31}{64}$	0·484375	$\frac{13}{16}$	0·8125
$\frac{11}{64}$	0·171875	$\frac{1}{2}$	0·500	$\frac{53}{64}$	0·828125
$\frac{3}{16}$	0·1875	$\frac{33}{64}$	0·515625	$\frac{27}{32}$	0·84375
$\frac{13}{64}$	0·203125	$\frac{17}{32}$	0·53125	$\frac{55}{64}$	0·859375
$\frac{7}{32}$	0·21875	$\frac{35}{64}$	0·546875	$\frac{7}{8}$	0·875
$\frac{15}{64}$	0·234375	$\frac{9}{16}$	0·5625	$\frac{57}{64}$	0·890625
$\frac{1}{4}$	0·250	$\frac{37}{64}$	0·578125	$\frac{29}{32}$	0·90625
$\frac{17}{64}$	0·265625	$\frac{19}{32}$	0·59375	$\frac{59}{64}$	0·921875
$\frac{9}{32}$	0·28125	$\frac{39}{64}$	0·609375	$\frac{15}{16}$	0·9375
$\frac{19}{64}$	0·296875	$\frac{5}{8}$	0·625	$\frac{61}{64}$	0·953125
$\frac{5}{16}$	0·3125	$\frac{41}{64}$	0·640625	$\frac{31}{32}$	0·96875
$\frac{21}{64}$	0·328125	$\frac{21}{32}$	0·65625	$\frac{63}{64}$	0·984375

LOGARITHMS.

No.	Log.	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
1·0	·0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
1·1	·0414	0453	0492	0531	0569	0607	0615	0682	0719	0755	4	8	11	15	19	23	26	30	34
1·2	·0792	0828	0864	0899	0934	0969	1004	1038	0172	1106	3	7	10	14	17	21	24	28	31
1·3	·1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
1·4	·1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
1·5	·1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
1·6	·2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
1·7	·2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
1·8	·2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
1·9	·2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
2·0	·3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
2·1	·3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
2·2	·3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
2·3	·3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
2·4	·3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
2·5	·3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
2·6	·4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
2·7	·4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
2·8	·4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
2·9	·4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
3·0	·4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
3·1	·4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
3·2	·5051	5065	5079	5092	5105	5119	5132	5145	5159	517	1	3	4	5	7	8	9	11	12
3·3	·5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
3·4	·5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
3·5	·5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
3·6	·5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
3·7	·5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
3·8	·5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
3·9	·5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
4·0	·6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
4·1	·6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
4·2	·6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
4·3	·6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
4·4	·6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
4·5	·6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
4·6	·6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
4·7	·6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
4·8	·6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
4·9	·6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
5·0	·6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
5·1	·7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
5·2	·7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
5·3	·7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
5·4	·7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7

No.	Log.	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
5·5	·7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
5·6	·7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
5·7	·7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
5·8	·7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
5·9	·7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
6·0	·7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
6·1	·7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
6·2	·7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
6·3	·7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
6·4	·8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
6·5	·8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
6·6	·8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
6·7	·8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
6·8	·8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
6·9	·8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
7·0	·8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
7·1	·8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
7·2	·8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
7·3	·8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
7·4	·8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
7·5	·8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
7·6	·8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
7·7	·8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
7·8	·8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
7·9	·8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
8·0	·9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
8·1	·9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
8·2	·9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
8·3	·9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
8·4	·9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
8·5	·9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
8·6	·9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
8·7	·9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
8·8	·9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
8·9	·9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
9·0	·9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
9·1	·9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
9·2	·9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
9·3	·9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
9·4	·9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
9·5	·9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
9·6	·9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
9·7	·9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	4	4	4
9·8	·9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
9·9	·9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4

ANTI-LOGARITHMS.

Log.	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
·00	1000	1002	1005	1007	1009	1012	1014	1016	1019	1021	0	0	1	1	1	1	2	2	2
·01	1023	1026	1028	1030	1033	1035	1038	1040	1042	1045	0	0	1	1	1	1	2	2	2
·02	1047	1050	1052	1054	1057	1059	1062	1064	1067	1069	0	0	1	1	1	1	2	2	2
·03	1072	1074	1076	1079	1081	1084	1086	1089	1091	1094	0	0	1	1	1	1	2	2	2
·04	1096	1099	1102	1104	1107	1109	1112	1114	1117	1119	0	1	1	1	1	2	2	2	2
·05	1122	1125	1127	1130	1132	1135	1138	1140	1143	1146	0	1	1	1	1	2	2	2	2
·06	1148	1151	1153	1156	1159	1161	1164	1167	1169	1172	0	1	1	1	1	2	2	2	2
·07	1175	1178	1180	1183	1186	1189	1191	1194	1197	1199	0	1	1	1	1	2	2	2	2
·08	1202	1205	1208	1211	1213	1216	1219	1222	1225	1227	0	1	1	1	1	2	2	2	3
·09	1230	1233	1236	1239	1242	1245	1247	1250	1253	1256	0	1	1	1	1	2	2	2	3
·10	1259	1262	1265	1268	1271	1274	1276	1279	1282	1285	0	1	1	1	1	2	2	2	3
·11	1288	1291	1294	1297	1300	1303	1306	1309	1312	1315	0	1	1	1	2	2	2	2	3
·12	1318	1321	1324	1327	1330	1334	1337	1340	1343	1346	0	1	1	1	2	2	2	2	3
·13	1349	1352	1355	1358	1361	1365	1368	1371	1374	1377	0	1	1	1	2	2	2	3	3
·14	1380	1384	1387	1390	1393	1396	1400	1403	1406	1409	0	1	1	1	2	2	2	3	3
·15	1413	1416	1419	1422	1426	1429	1432	1435	1439	1442	0	1	1	1	2	2	2	3	3
·16	1445	1449	1452	1455	1459	1462	1466	1469	1472	1476	0	1	1	1	2	2	2	3	3
·17	1479	1483	1486	1489	1493	1496	1500	1503	1507	1510	0	1	1	1	2	2	2	3	3
·18	1514	1517	1521	1524	1528	1531	1535	1538	1542	1545	0	1	1	1	2	2	2	3	3
·19	1549	1552	1556	1560	1563	1567	1570	1574	1578	1581	0	1	1	1	2	2	3	3	3
·20	1585	1589	1592	1596	1600	1603	1607	1611	1614	1618	0	1	1	1	2	2	3	3	3
·21	1622	1626	1629	1633	1637	1641	1644	1648	1652	1656	0	1	1	2	2	2	3	3	3
·22	1660	1663	1667	1671	1675	1679	1683	1687	1690	1694	0	1	1	2	2	2	3	3	3
·23	1698	1702	1706	1710	1714	1718	1722	1726	1730	1734	0	1	1	2	2	2	3	3	4
·24	1738	1742	1746	1750	1754	1758	1762	1766	1770	1774	0	1	1	2	2	2	3	3	4
·25	1778	1782	1786	1791	1795	1799	1803	1807	1811	1816	0	1	1	2	2	2	3	3	4
·26	1820	1824	1828	1832	1837	1841	1845	1849	1854	1858	0	1	1	2	2	3	3	3	4
·27	1862	1866	1871	1875	1879	1884	1888	1892	1897	1901	0	1	1	2	2	3	3	3	4
·28	1905	1910	1914	1919	1923	1928	1932	1936	1941	1945	0	1	1	2	2	3	3	4	4
·29	1950	1954	1959	1963	1968	1972	1977	1982	1986	1991	0	1	1	2	2	3	3	4	4
·30	1995	2000	2004	2009	2014	2018	2023	2028	2032	2037	0	1	1	2	2	3	3	4	4
·31	2042	2046	2051	2056	2061	2065	2070	2075	2080	2084	0	1	1	2	2	3	3	4	4
·32	2089	2094	2099	2104	2109	2113	2118	2123	2128	2133	0	1	1	2	2	3	3	4	4
·33	2138	2143	2148	2153	2158	2163	2168	2173	2178	2183	0	1	1	2	2	3	3	4	4
·34	2188	2193	2198	2203	2208	2213	2218	2223	2228	2234	1	1	2	2	3	3	4	4	5
·35	2239	2244	2249	2254	2259	2265	2270	2275	2280	2286	1	1	2	2	3	3	4	4	5
·36	2291	2296	2301	2307	2312	2317	2323	2328	2333	2339	1	1	2	2	3	3	4	4	5
·37	2344	2350	2355	2360	2366	2371	2377	2382	2388	2393	1	1	2	2	3	3	4	4	5
·38	2399	2404	2410	2415	2421	2427	2432	2438	2443	2449	1	1	2	2	3	3	4	4	5
·39	2455	2460	2466	2472	2477	2483	2489	2495	2500	2506	1	1	2	2	3	3	4	5	5
·40	2512	2518	2523	2529	2535	2541	2547	2553	2559	2564	1	1	2	2	3	4	4	5	5
·41	2570	2576	2582	2588	2594	2600	2606	2612	2618	2624	1	1	2	2	3	4	4	5	5
·42	2630	2636	2642	2649	2655	2661	2667	2673	2679	2685	1	1	2	2	3	4	4	5	6
·43	2692	2698	2704	2710	2716	2723	2729	2735	2742	2748	1	1	2	3	3	4	4	5	6
·44	2754	2761	2767	2773	2780	2786	2793	2799	2805	2812	1	1	2	3	3	4	4	5	6
·45	2818	2825	2831	2838	2844	2851	2858	2864	2871	2877	1	1	2	3	3	4	5	5	6
·46	2884	2891	2897	2904	2911	2917	2924	2931	2938	2944	1	1	2	3	3	4	5	5	6
·47	2951	2958	2965	2972	2979	2985	2992	2999	3006	3013	1	1	2	3	3	4	5	5	6
·48	3020	3027	3034	3041	3048	3055	3062	3069	3076	3083	1	1	2	3	4	4	5	6	6
·49	3090	3097	3105	3112	3119	3126	3133	3141	3148	3155	1	1	2	3	4	4	5	6	6

ANTI-LOGARITHMS.

Log.	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
·50	3162	3170	3177	3184	3192	3199	3206	3214	3221	3228	1	1	2	3	4	4	5	6	7
·51	3236	3243	3251	3258	3266	3273	3281	3289	3296	3304	1	2	2	3	4	5	5	6	7
·52	3311	3319	3327	3334	3342	3350	3357	3365	3373	3381	1	2	2	3	4	5	5	6	7
·53	3388	3396	3404	3412	3420	3428	3436	3443	3451	3459	1	2	2	3	4	5	6	6	7
·54	3467	3475	3483	3491	3499	3508	3516	3524	3532	3540	1	2	2	3	4	5	6	6	7
·55	3548	3556	3565	3573	3581	3589	3597	3606	3614	3622	1	2	2	3	4	5	6	7	7
·56	3631	3639	3648	3656	3664	3673	3681	3690	3698	3707	1	2	3	3	4	5	6	7	8
·57	3715	3724	3733	3741	3750	3758	3767	3776	3784	3793	1	2	3	3	4	5	6	7	8
·58	3802	3811	3819	3828	3837	3846	3855	3864	3873	3882	1	2	3	4	4	5	6	7	8
·59	3890	3899	3908	3917	3926	3936	3945	3954	3963	3972	1	2	3	4	5	5	6	7	8
·60	3981	3990	3999	4009	4018	4027	4036	4046	4055	4064	1	2	3	4	5	6	6	7	8
·61	4074	4083	4093	4102	4111	4121	4130	4140	4150	4159	1	2	3	4	5	6	7	8	9
·62	4169	4178	4188	4198	4207	4217	4227	4236	4246	4256	1	2	3	4	5	6	7	8	9
·63	4266	4276	4285	4295	4305	4315	4325	4335	4345	4355	1	2	3	4	5	6	7	8	9
·64	4365	4375	4385	4395	4406	4416	4426	4436	4446	4457	1	2	3	4	5	6	7	8	9
·65	4467	4477	4487	4498	4508	4519	4529	4539	4550	4560	1	2	3	4	5	6	7	8	9
·66	4571	4581	4592	4603	4613	4624	4634	4645	4656	4667	1	2	3	4	5	6	7	9	10
·67	4677	4688	4699	4710	4721	4732	4742	4753	4764	4775	1	2	3	4	5	7	8	9	10
·68	4786	4797	4808	4819	4831	4842	4853	4864	4875	4887	1	2	3	4	6	7	8	9	10
·69	4898	4909	4920	4932	4943	4955	4966	4977	4989	5000	1	2	3	5	6	7	8	9	10
·70	5012	5023	5035	5047	5058	5070	5082	5093	5105	5117	1	2	4	5	6	7	8	9	11
·71	5129	5140	5152	5164	5176	5188	5200	5212	5224	5236	1	2	4	5	6	7	8	10	11
·72	5248	5260	5272	5284	5297	5309	5321	5333	5346	5358	1	2	4	5	6	7	9	10	11
·73	5370	5383	5395	5408	5420	5433	5445	5458	5470	5483	1	3	4	5	6	8	9	10	11
·74	5495	5508	5521	5534	5546	5559	5572	5585	5598	5610	1	3	4	5	6	8	9	10	12
·75	5623	5636	5649	5662	5675	5689	5702	5715	5728	5741	1	3	4	5	7	8	9	10	12
·76	5754	5768	5781	5794	5808	5821	5834	5848	5861	5875	1	3	4	5	7	8	9	11	12
·77	5888	5902	5916	5929	5943	5957	5970	5984	5998	6012	1	3	4	5	7	8	10	11	12
·78	6026	6039	6053	6067	6081	6095	6109	6124	6138	6152	1	3	4	6	7	8	10	11	13
·79	6166	6180	6194	6209	6223	6237	6252	6266	6281	6295	1	3	4	6	7	9	10	11	13
·80	6310	6324	6339	6353	6368	6383	6397	6412	6427	6442	1	3	4	6	7	9	10	12	13
·81	6457	6471	6486	6501	6516	6531	6546	6561	6577	6592	2	3	5	6	8	9	11	12	14
·82	6607	6622	6637	6653	6668	6683	6699	6714	6730	6745	2	3	5	6	8	9	11	12	14
·83	6761	6776	6792	6808	6823	6839	6855	6871	6887	6902	2	3	5	6	8	9	11	13	14
·84	6918	6934	6950	6966	6982	6998	7015	7031	7047	7063	2	3	5	6	8	10	11	13	15
·85	7079	7096	7112	7129	7145	7161	7178	7194	7211	7228	2	3	5	7	8	10	12	13	15
·86	7244	7261	7278	7295	7311	7328	7345	7362	7379	7396	2	3	5	7	8	10	12	13	15
·87	7413	7430	7447	7464	7482	7499	7516	7534	7551	7568	2	3	5	7	9	10	12	14	16
·88	7586	7603	7621	7638	7656	7674	7691	7709	7727	7745	2	4	5	7	9	11	12	14	16
·89	7762	7780	7798	7816	7834	7852	7870	7889	7907	7925	2	4	5	7	9	11	13	14	16
·90	7943	7962	7980	7998	8017	8035	8054	8072	8091	8110	2	4	6	7	9	11	13	15	17
·91	8128	8147	8166	8185	8204	8222	8241	8260	8279	8299	2	4	6	8	9	11	13	15	17
·92	8318	8337	8356	8375	8395	8414	8433	8453	8472	8492	2	4	6	8	10	12	14	15	17
·93	8511	8531	8551	8570	8590	8610	8630	8650	8670	8690	2	4	6	8	10	12	14	16	18
·94	8710	8730	8750	8770	8790	8810	8831	8851	8872	8892	2	4	6	8	10	12	14	16	18
·95	8913	8933	8954	8974	8995	9016	9036	9057	9078	9099	2	4	6	8	10	12	15	17	19
·96	9120	9141	9162	9183	9204	9226	9247	9268	9290	9311	2	4	6	8	11	13	15	17	19
·97	9333	9354	9376	9397	9419	9441	9462	9484	9506	9528	2	4	7	9	11	13	15	17	20
·98	9550	9572	9594	9616	9638	9661	9683	9705	9727	9750	2	4	7	9	11	13	16	18	20
·99	9772	9795	9817	9840	9863	9886	9908	9931	9954	9977	2	5	7	9	11	14	16	18	20

NATURAL SINES.

Angle.	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′
0°	·0000	·0017	·0035	·0052	·0070	·0087	·0105	·0122	·0140	·0157	3	6	9	12	15
1°	·0175	·0192	·0209	·0227	·0244	·0262	·0279	·0297	·0314	·0332	3	6	9	12	15
2°	·0349	·0366	·0384	·0401	·0419	·0436	·0454	·0471	·0488	·0506	3	6	9	12	15
3°	·0523	·0541	·0558	·0576	·0593	·0610	·0628	·0645	·0663	·0680	3	6	9	12	15
4°	·0698	·0715	·0732	·0750	·0767	·0785	·0802	·0819	·0837	·0854	3	6	9	12	14
5°	·0872	·0889	·0906	·0924	·0941	·0958	·0976	·0993	·1011	·1028	3	6	9	12	14
6°	·1045	·1063	·1080	·1097	·1115	·1132	·1149	·1167	·1184	·1201	3	6	9	12	14
7°	·1219	·1236	·1253	·1271	·1288	·1305	·1323	·1340	·1357	·1374	3	6	9	12	14
8°	·1392	·1409	·1426	·1444	·1461	·1478	·1495	·1513	·1530	·1547	3	6	9	12	14
9°	·1564	·1582	·1599	·1616	·1633	·1650	·1668	·1685	·1702	·1719	3	6	9	12	14
10°	·1736	·1754	·1771	·1788	·1805	·1822	·1840	·1857	·1874	·1891	3	6	9	11	14
11°	·1908	·1925	·1942	·1959	·1977	·1994	·2011	·2028	·2045	·2062	3	6	9	11	14
12°	·2079	·2096	·2113	·2130	·2147	·2164	·2181	·2198	·2215	·2233	3	6	9	11	14
13°	·2250	·2267	·2284	·2300	·2317	·2334	·2351	·2368	·2385	·2402	3	6	8	11	14
14°	·2419	·2436	·2453	·2470	·2487	·2504	·2521	·2538	·2554	·2571	3	6	8	11	14
15°	·2588	·2605	·2622	·2639	·2656	·2672	·2689	·2706	·2723	·2740	3	6	8	11	14
16°	·2756	·2773	·2790	·2807	·2823	·2840	·2857	·2874	·2890	·2907	3	6	8	11	14
17°	·2924	·2940	·2957	·2974	·2990	·3007	·3024	·3040	·3057	·3074	3	6	8	11	14
18°	·3090	·3107	·3123	·3140	·3156	·3173	·3190	·3206	·3223	·3239	3	6	8	11	14
19°	·3256	·3272	·3289	·3305	·3322	·3338	·3355	·3371	·3387	·3404	3	5	8	11	14
20°	·3420	·3437	·3453	·3469	·3486	·3502	·3518	·3535	·3551	·3567	3	5	8	11	14
21°	·3584	·3600	·3616	·3633	·3649	·3665	·3681	·3697	·3714	·3730	3	5	8	11	14
22°	·3746	·3762	·3778	·3795	·3811	·3827	·3843	·3859	·3875	·3891	3	5	8	11	14
23°	·3907	·3923	·3939	·3955	·3971	·3987	·4003	·4019	·4035	·4051	3	5	8	11	14
24°	·4067	·4083	·4099	·4115	·4131	·4147	·4163	·4179	·4195	·4210	3	5	8	11	13
25°	·4226	·4242	·4258	·4274	·4289	·4305	·4321	·4337	·4352	·4368	3	5	8	11	13
26°	·4384	·4399	·4415	·4431	·4446	·4462	·4478	·4493	·4509	·4524	3	5	8	10	13
27°	·4540	·4555	·4571	·4586	·4602	·4617	·4633	·4648	·4664	·4679	3	5	8	10	13
28°	·4695	·4710	·4726	·4741	·4756	·4772	·4787	·4802	·4818	·4833	3	5	8	10	13
29°	·4848	·4863	·4879	·4894	·4909	·4924	·4939	·4955	·4970	·4985	3	5	8	10	13
30°	·5000	·5015	·5030	·5045	·5060	·5075	·5090	·5105	·5120	·5135	3	5	8	10	13
31°	·5150	·5165	·5180	·5195	·5210	·5225	·5240	·5255	·5270	·5284	2	5	7	10	12
32°	·5299	·5314	·5329	·5344	·5358	·5373	·5388	·5402	·5417	·5432	2	5	7	10	12
33°	·5446	·5461	·5476	·5490	·5505	·5519	·5534	·5548	·5563	·5577	2	5	7	10	12
34°	·5592	·5606	·5621	·5635	·5650	·5664	·5678	·5693	·5707	·5721	2	5	7	10	12
35°	·5736	·5750	·5764	·5779	·5793	·5807	·5821	·5835	·5850	·5864	2	5	7	9	12
36°	·5878	·5892	·5906	·5920	·5934	·5948	·5962	·5976	·5990	·6004	2	5	7	9	12
37°	·6018	·6032	·6046	·6060	·6074	·6088	·6101	·6115	·6129	·6143	2	5	7	9	12
38°	·6157	·6170	·6184	·6198	·6211	·6225	·6239	·6252	·6266	·6280	2	5	7	9	11
39°	·6293	·6307	·6320	·6334	·6347	·6361	·6374	·6388	·6401	·6414	2	4	7	9	11
40°	·6428	·6441	·6455	·6468	·6481	·6494	·6508	·6521	·6534	·6547	2	4	7	9	11
41°	·6561	·6574	·6587	·6600	·6613	·6626	·6639	·6652	·6665	·6678	2	4	7	9	11
42°	·6691	·6704	·6717	·6730	·6743	·6756	·6759	·6782	·6794	·6807	2	4	6	9	11
43°	·6820	·6833	·6845	·6858	·6871	6884	·6896	·6909	·6921	·6934	2	4	6	8	11
44°	·6947	·6959	·6972	·6984	·6997	·7009	·7022	·7034	·7046	·7059	2	4	6	8	10

NATURAL SINES.

Angle.	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′
45°	·7071	·7083	·7096	·7108	·7120	·7133	·7145	·7157	·7169	·7181	2	4	6	8	10
46°	·7193	·7206	·7218	·7230	·7242	·7254	·7266	·7278	·7290	·7302	2	4	6	8	10
47°	·7314	·7325	·7337	·7349	·7361	·7373	·7385	·7396	·7408	·7420	2	4	6	8	10
48°	·7431	·7443	·7455	·7466	·7478	·7490	·7501	·7513	·7524	·7536	2	4	6	8	10
49°	·7547	·7559	·7570	·7581	·7593	·7604	·7615	·7627	·7638	·7649	2	4	6	8	9
50°	·7660	·7672	·7683	·7694	·7705	·7716	·7727	·7738	·7749	·7760	2	4	6	7	9
51°	·7771	·7782	·7793	·7804	·7815	·7826	·7837	·7848	·7859	·7869	2	4	5	7	9
52°	·7880	·7891	·7902	·7912	·7923	·7934	·7944	·7955	·7965	·7976	2	4	5	7	9
53°	·7986	·7997	·8007	·8018	·8028	·8039	·8049	·8059	·8070	·8080	2	3	5	7	9
54°	·8090	·8100	·8111	·8121	·8131	·8141	·8151	·8161	·8171	·8181	2	3	5	7	8
55°	·8192	·8202	·8211	·8221	·8231	·8241	·8251	·8261	·8271	·8281	2	3	5	7	8
56°	·8290	·8300	·8310	·8320	·8329	·8339	·8348	·8358	·8368	·8377	2	3	5	6	8
57°	·8387	·8396	·8406	·8415	·8425	·8434	·8443	·8453	·8462	·8471	2	3	5	6	8
58°	·8480	·8490	·8499	·8508	·8517	·8526	·8536	·8545	·8554	·8563	2	3	5	6	8
59°	·8572	·8581	·8590	·8599	·8607	·8616	·8625	·8634	·8643	·8652	1	3	4	6	7
60°	·8660	·8669	·8678	·8686	·8695	·8704	·8712	·8721	·8729	·8738	1	3	4	6	7
61°	·8746	·8755	·8763	·8771	·8780	·8788	·8796	·8805	·8813	·8821	1	3	4	6	7
62°	·8829	·8838	·8846	·8854	·8862	·8870	·8878	·8886	·8894	·8902	1	3	4	5	7
63°	·8910	·8918	·8926	·8934	·8942	·8949	·8957	·8965	·8973	·8980	1	3	4	5	6
64°	·8988	·8996	·9003	·9011	·9018	·9026	·9033	·9041	·9048	·9056	1	3	4	5	6
65°	·9063	·9070	·9078	·9085	·9092	·9100	·9107	·9114	·9121	·9128	1	2	4	5	6
66°	·9135	·9143	·9150	·9157	·9164	·9171	·9178	·9184	·9191	·9198	1	2	3	5	6
67°	·9205	·9212	·9219	·9225	·9232	·9239	·9245	·9252	·9259	·9265	1	2	3	4	6
68°	·9272	·9278	·9285	·9291	·9298	·9304	·9311	·9317	·9323	·9330	1	2	3	4	5
69°	·9336	·9342	·9348	·9354	·9361	·9367	·9373	·9379	·9385	·9391	1	2	3	4	5
70°	·9397	·9403	·9409	·9415	·9421	·9426	·9432	·9438	·9444	·9449	1	2	3	4	5
71°	·9455	·9461	·9466	·9472	·9478	·9483	·9489	·9494	·9500	·9505	1	2	3	4	5
72°	·9511	·9516	·9521	·9527	·9532	·9537	·9542	·9548	·9553	·9558	1	2	3	3	4
73°	·9563	·9568	·9573	·9578	·9583	·9588	·9593	·9598	·9603	·9608	1	2	2	3	4
74°	·9613	·9617	·9622	·9627	·9632	·9636	·9641	·9646	·9650	·9655	1	2	2	3	4
75°	·9659	·9664	·9668	·9673	·9677	·9681	·9686	·9690	·9694	·9699	1	1	2	3	4
76°	·9703	·9707	·9711	·9715	·9720	·9724	·9728	·9732	·9736	·9740	1	1	2	3	3
77°	9744	·9748	·9751	·9755	·9759	·9763	·9767	·9770	·9774	·9778	1	1	2	3	3
78°	·9781	·9785	·9789	·9792	·9796	·9799	·9803	·9806	·9810	·9813	1	1	2	2	3
79°	·9816	·9820	·9823	·9826	·9829	·9833	·9836	·9839	·9842	·9845	1	1	2	2	3
80°	·9848	·9851	·9854	·9857	·9860	·9863	·9866	·9869	·9871	·9874	0	1	1	2	2
81°	·9877	·9880	·9882	·9885	·9888	·9890	·9893	·9895	·9898	·9900	0	1	1	2	2
82°	·9903	·9905	·9907	·9910	·9912	·9914	·9917	·9919	·9921	·9923	0	1	1	2	2
83°	·9925	·9928	·9930	·9932	·9934	·9936	·9938	·9940	·9942	·9943	0	1	1	1	2
84°	·9945	·9947	·9949	·9951	·9952	·9954	·9956	·9957	·9959	·9960	0	1	1	1	1
85°	·9962	·9963	·9965	·9966	·9968	·9969	·9971	·9972	·9973	·9974	0	0	1	1	1
86°	·9976	·9977	·9978	·9979	·9980	·9981	·9982	·9983	·9984	·9985	0	0	1	1	1
87°	·9986	·9987	·9988	·9989	·9990	·9990	·9991	·9992	·9993	·9993	0	0	0	1	1
88°	·9994	·9995	·9995	·9996	·9996	·9997	·9997	·9997	·9998	·9998	0	0	0	0	0
89°	·9998	·9999	·9999	·9999	·9999	1·000	1·000	1·000	1·000	1·000	0	0	0	0	0

NATURAL COSINES.

Subtract Differences.

Angle.	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′
0°	1·0000	1·000	1·000	1·000	1·000	1·000	·9999	·9999	·9999	·9999	0	0	0	0	0
1°	·9998	·9998	·9998	·9997	·9997	·9997	·9996	·9996	·9995	·9995	0	0	0	0	0
2°	·9994	·9993	·9993	·9992	·9991	·9990	·9990	·9989	·9988	·9987	0	0	0	0	0
3°	·9986	·9985	·9984	·9983	·9982	·9981	·9980	·9979	·9978	·9977	0	0	1	1	1
4°	·9976	·9974	·9973	·9972	·9971	·9969	·9968	·9966	·9965	·9963	0	0	1	1	1
5°	·9962	·9960	·9959	·9957	·9956	·9954	·9952	·9951	·9949	·9947	0	1	1	1	1
6°	·9945	·9943	·9942	·9940	·9938	·9936	·9934	·9932	·9930	·9928	0	1	1	1	2
7°	·9925	·9923	·9921	·9919	·9917	·9914	·9912	·9910	·9907	·9905	0	1	1	2	2
8°	·9903	·9900	·9898	·9895	·9893	·9890	·9888	·9885	·9882	·9880	0	1	1	2	2
9°	·9877	·9874	·9871	·9869	·9866	·9863	·9860	·9857	·9854	·9851	0	1	1	2	2
10°	·9848	·9845	·9842	·9839	·9836	·9833	·9829	·9826	·9823	·9820	1	1	2	2	3
11°	·9816	·9813	·9810	·9806	·9803	·9799	·9796	·9792	·9789	·9785	1	1	2	2	3
12°	·9781	·9778	·9774	·9770	·9767	·9763	·9759	·9755	·9751	·9748	1	1	2	3	3
13°	·9744	·9740	·9736	·9732	·9728	·9724	·9720	·9715	·9711	·9707	1	1	2	3	3
14°	·9703	·9699	·9694	·9690	·9686	·9681	·9677	·9673	·9668	·9664	1	1	2	3	4
15°	·9659	·9655	·9650	·9646	·9641	·9636	·9632	·9627	·9622	·9617	1	2	2	3	4
16°	·9613	·9608	·9603	·9598	·9593	·9588	·9583	·9578	·9573	·9568	1	2	2	3	4
17°	·9563	·9558	·9553	·9548	·9542	·9537	·9532	·9527	·9521	·9516	1	2	3	4	4
18°	·9511	·9505	·9500	·9494	·9489	·9483	·9478	·9472	·9466	·9461	1	2	3	4	5
19°	·9455	·9449	·9444	·9438	·9432	·9426	·9421	·9415	·9409	·9403	1	2	3	4	5
20°	·9397	·9391	·9385	·9379	·9373	·9367	·9361	·9354	·9348	·9342	1	2	3	4	5
21°	·9336	·9330	·9323	·9317	·9311	·9304	·9298	·9291	·9285	·9278	1	2	3	4	5
22°	·9272	·9265	·9259	·9252	·9245	·9239	·9232	·9225	·9219	·9212	1	2	3	4	6
23°	·9205	·9198	·9191	·9184	·9178	·9171	·9164	·9157	·9150	·9143	1	2	3	5	6
24°	·9135	·9128	·9121	·9114	·9107	·9100	·9092	·9085	·9078	·9070	1	2	4	5	6
25°	·9063	·9056	·9048	·9041	·9033	·9026	·9018	·9011	·9003	·8996	1	3	4	5	6
26°	·8988	·8980	·8973	·8965	·8957	·8949	·8942	·8934	·8926	·8918	1	3	4	5	6
27°	·8010	·8902	·8894	·8886	·8878	·8870	·8862	·8854	·8846	·8838	1	3	4	5	7
28°	·8829	·8821	·8813	·8805	·8796	·8788	·8780	·8771	·8763	·8755	1	3	4	6	7
29°	·8746	·8738	·8729	·8721	·8712	·8704	·8695	·8686	·8678	·8669	1	3	4	6	7
30°	·8660	·8652	·8643	·8634	·8625	·8616	·8607	·8599	·8590	·8581	1	3	4	6	7
31°	·8572	·8563	·8554	·8545	·8536	·8526	·8517	·8508	·8499	·8490	2	3	5	6	8
32°	·8480	·8471	·8462	·8453	·8443	·8434	·8425	·8415	·8406	·8396	2	3	5	6	8
33°	·8387	·8377	·8368	·8358	·8348	·8339	·8329	·8320	·8310	·8300	2	3	5	6	8
34°	·8290	·8281	·8271	·8261	·8251	·8241	·8231	·8221	·8211	·8202	2	3	5	7	8
35°	·8192	·8181	·8171	·8161	·8151	·8141	·8131	·8121	·8111	·8100	2	3	5	7	8
36°	·8090	·8080	·8070	·8059	·8049	·8039	·8028	·8018	·8007	·7997	2	3	5	7	9
37°	·7986	·7976	·7965	·7955	·7944	·7934	·7923	·7912	·7902	·7891	2	4	5	7	9
38°	·7880	·7869	·7859	·7848	·7837	·7826	·7815	·7804	·7793	·7782	2	4	5	7	9
39°	·7771	·7760	·7749	·7738	·7727	·7716	·7705	·7694	·7683	·7672	2	4	6	7	9
40°	·7660	·7649	·7638	·7627	·7615	·7604	·7593	·7581	·7570	·7559	2	4	6	8	9
41°	·7547	·7536	·7524	·7513	·7501	·7490	·7478	·7466	·7455	·7443	2	4	6	8	10
42°	·7431	·7420	·7408	·7396	·7385	·7373	·7361	·7349	·7337	·7325	2	4	6	8	10
43°	·7314	·7302	·7290	·7278	·7266	·7254	·7242	·7230	·7218	·7206	2	4	6	8	10
44°	·7193	·7181	·7169	·7157	·7145	·7133	·7120	·7108	·7096	·7083	2	4	6	8	10

Angle.	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′
45°	·7071	·7059	·7046	·7034	·7022	·7009	·6997	·6984	·6972	·6959	2	4	6	8	10
46°	·6947	·6934	·6921	·6909	·6896	·6884	·6871	·6858	·6845	·6833	2	4	6	8	11
47°	·6820	·6807	·6794	·6782	·6769	·6756	·6743	·6730	·6717	·6704	2	4	6	9	11
48°	·6691	·6678	·6665	·6652	·6639	·6626	·6613	·6600	·6587	·6574	2	4	7	9	11
49°	·6561	·6547	·6534	·6521	·6508	·6494	·6481	·6468	·6455	·6441	2	4	7	9	11
50°	·6428	·6414	·6401	·6388	·6374	·6361	·6347	·6334	·6320	·6307	2	4	7	9	11
51°	·6293	·6280	·6266	·6252	·6239	·6225	·6211	·6198	·6184	·6170	2	5	7	9	11
52°	·6157	·6143	·6129	·6115	·6101	·6088	·6074	·6060	·6046	·6032	2	5	7	9	12
53°	·6018	·6004	·5990	·5976	·5962	·5948	·5934	·5920	·5906	·5892	2	5	7	9	12
54°	·5878	·5864	·5850	·5835	·5821	·5807	·5793	·5779	·5764	·5750	2	5	7	9	12
55°	·5736	·5721	·5707	·5693	·5678	·5664	·5650	·5635	·5621	·5606	2	5	7	10	12
56°	·5592	·5577	·5563	·5548	·5534	·5519	·5505	·5490	·5476	·5461	2	5	7	10	12
57°	·5446	·5432	·5417	·5402	·5388	·5373	·5358	·5344	·5329	·5314	2	5	7	10	12
58°	·5299	·5284	·5270	·5255	·5240	·5225	·5210	·5195	·5180	·5165	2	5	7	10	12
59°	·5150	·5135	·5120	·5105	·5090	·5075	·5060	·5045	·5030	·5015	3	5	8	10	13
60°	·5000	·4985	·4970	·4955	·4939	·4924	·4909	·4894	·4879	·4863	3	5	8	10	13
61°	·4848	·4833	·4818	·4802	·4787	·4772	·4756	·4741	·4726	·4710	3	5	8	10	13
62°	·4695	·4679	·4664	·4648	·4633	·4617	·4602	·4586	·4571	·4555	3	5	8	10	13
63°	·4540	·4524	·4509	·4493	·4478	·4462	·4446	·4431	·4415	·4399	3	5	8	10	13
64°	·4384	·4368	·4352	·4337	·4321	·4305	·4289	·4274	·4258	·4242	3	5	8	11	13
65°	·4226	·4210	·4195	·4179	·4163	·4147	·4131	·4115	·4099	·4083	3	5	8	11	13
66°	·4067	·4051	·4035	·4019	·4003	·3987	·3971	·3955	·3939	·3923	3	5	8	11	13
67°	·3907	·3891	·3875	·3859	·3843	·3827	·3811	·3795	·3778	·3762	3	5	8	11	13
68°	·3746	·3730	·3714	·3697	·3681	·3665	·3649	·3633	·3616	·3600	3	5	8	11	14
69°	·3584	·3567	·3551	·3535	·3518	·3502	·3486	·3469	·3453	·3437	3	5	8	11	14
70°	·3420	·3404	·3387	·3371	·3355	·3338	·3322	·3305	·3289	·3272	3	5	8	11	14
71°	·3256	·3239	·3223	·3206	·3190	·3173	·3156	·3140	·3123	·3107	3	6	8	11	14
72°	·3090	·3074	·3057	·3040	·3024	·3007	·2990	·2974	·2957	·2940	3	6	8	11	14
73°	·2924	·2907	·2890	·2874	·2857	·2840	·2823	·2807	·2790	·2773	3	6	8	11	14
74°	·2756	·2740	·2723	·2706	·2689	·2672	·2656	·2639	·2622	·2605	3	6	8	11	14
75°	·2588	·2571	·2554	·2538	·2521	·2504	·2487	·2470	·2453	·2436	3	6	8	11	14
76°	·2419	·2402	·2385	·2368	·2351	·2334	·2317	·2300	·2284	·2267	3	6	8	11	14
77°	·2250	·2233	·2215	·2198	·2181	·2164	·2147	·2130	·2113	·2096	3	6	9	11	14
78°	·2079	·2062	·2045	·2028	·2011	·1994	·1977	·1959	·1942	·1925	3	6	9	11	14
79°	·1908	·1891	·1874	·1857	·1840	·1822	·1805	·1788	·1771	·1754	3	6	9	11	14
80°	·1736	·1719	·1702	·1685	·1668	·1650	·1633	·1616	·1599	·1582	3	6	9	11	14
81°	·1564	·1547	·1530	·1513	·1495	·1478	·1461	·1444	·1426	·1409	3	6	9	12	14
82°	·1392	·1374	·1357	·1340	·1323	·1305	·1288	·1271	·1253	·1236	3	6	9	12	14
83°	·1219	·1201	·1184	·1167	·1149	·1132	·1115	·1097	·1080	·1063	3	6	9	12	14
84°	·1045	·1028	·1011	·0993	·0976	·0958	·0941	·0924	·0906	·0889	3	6	9	12	14
85°	·0872	·0854	·0837	·0819	·0802	·0785	·0767	·0750	·0732	·0715	3	6	9	12	14
86°	·0698	·0680	·0663	·0645	·0628	·0610	·0593	·0576	·0558	·0541	3	6	9	12	15
87°	·0523	·0506	·0488	·0471	·0454	·0436	·0419	·0401	·0384	·0366	3	6	9	12	15
88°	·0349	·0332	·0314	·0297	·0279	·0262	·0244	·0227	·0209	·0192	3	6	9	12	15
89°	·0175	·0157	·0140	·0122	·0105	·0087	·0070	·0052	·0035	·0017	3	6	9	12	15

NATURAL TANGENTS.

Angle.	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′
0°	0·0000	·0017	·0035	·0052	·0070	·0087	·0105	·0122	·0140	·0157	3	6	9	12	15
1°	0·0175	·0192	·0209	·0227	·0244	·0262	·0279	·0297	·0314	·0332	3	6	9	12	15
2°	0·0349	·0367	·0384	·0402	·0419	·0437	·0454	·0472	·0489	·0507	3	6	9	12	15
3°	0·0524	·0542	·0559	·0577	·0594	·0612	·0629	·0647	·0664	·0682	3	6	9	12	15
4°	0·0699	·0717	·0734	·0752	·0769	·0787	·0805	·0822	·0840	·0857	3	6	9	12	15
5°	0·0875	·0892	·0910	·0928	·0945	·0963	·0981	·0998	·1016	·1033	3	6	9	12	15
6°	0·1051	·1069	·1086	·1104	·1122	·1139	·1157	·1175	·1192	·1210	3	6	9	12	15
7°	0·1228	·1246	·1263	·1281	·1299	·1317	·1334	·1352	·1370	·1388	3	6	9	12	15
8°	0·1405	·1423	·1441	·1459	·1477	·1495	·1512	·1530	·1548	·1566	3	6	9	12	15
9°	0·1584	·1602	·1620	·1638	·1655	·1673	·1691	·1709	·1727	·1745	3	6	9	12	15
10°	0·1763	·1781	·1799	·1817	·1835	·1853	·1871	·1890	·1908	·1926	3	6	9	12	15
11°	0·1944	·1962	·1980	·1998	·2016	·2035	·2053	·2071	·2089	·2107	3	6	9	12	15
12°	0·2126	·2144	·2162	·2180	·2199	·2217	·2235	·2254	·2272	·2290	3	6	9	12	15
13°	0·2309	·2327	·2345	·2364	·2382	·2401	·2419	·2438	·2456	·2475	3	6	9	12	15
14°	0·2493	·2512	·2530	·2549	·2568	·2586	·2605	·2623	·2642	·2661	3	6	9	12	16
15°	0·2679	·2698	·2717	·2736	·2754	·2773	·2792	·2811	·2830	·2849	3	6	9	13	16
16°	0·2867	·2886	·2905	·2924	·2943	·2962	·2981	·3000	·3019	·3038	3	6	9	13	16
17°	0·3057	·3076	·3096	·3115	·3134	·3153	·3172	·3191	·3211	·3230	3	6	10	13	16
18°	0·3249	·3269	·3288	·3307	·3327	·3346	·3365	·3385	·3404	·3424	3	6	10	13	16
19°	0·3443	·3463	·3482	·3502	·3522	·3541	·3561	·3581	·3600	·3620	3	7	10	13	16
20°	0·3640	·3659	·3679	·3699	·3719	·3739	·3759	·3779	·3799	·3819	3	7	10	13	17
21°	0·3839	·3859	·3879	·3899	·3919	·3939	·3959	·3979	·4000	·4020	3	7	10	13	17
22°	0·4040	·4061	·4081	·4101	·4122	·4142	·4163	·4183	·4204	·4224	3	7	10	14	17
23°	0·4245	·4265	·4286	·4307	·4327	·4348	·4369	·4390	·4411	·4431	3	7	10	14	17
24°	0·4452	·4473	·4494	·4515	·4536	·4557	·4578	·4599	·4621	·4642	4	7	11	14	18
25°	0·4663	·4684	·4706	·4727	·4748	·4770	·4791	·4813	·4834	·4856	4	7	11	14	18
26°	0·4877	·4899	·4921	·4942	·4964	·4986	·5008	·5029	·5051	·5073	4	7	11	15	18
27°	0·5095	·5117	·5139	·5161	·5184	·5206	·5228	·5250	·5272	·5295	4	7	11	15	18
28°	0·5317	·5340	·5362	·5384	·5407	·5430	·5452	·5475	·5498	·5520	4	8	11	15	19
29°	0·5543	·5566	·5589	·5612	·5635	·5658	·5681	·5704	·5727	·5750	4	8	12	15	19
30°	0·5774	·5797	·5820	·5844	·5867	·5890	·5914	·5938	·5961	·5985	4	8	12	16	20
31°	0·6009	·6032	·6056	·6080	·6104	·6128	·6152	·6176	·6200	·6224	4	8	12	16	20
32°	0·6249	·6273	·6297	·6322	·6346	·6371	·6395	·6420	·6445	·6469	4	8	12	16	20
33°	0·6494	·6519	·6544	·6569	·6594	·6619	·6644	·6669	·6694	·6720	4	8	13	17	21
34°	0·6745	·6771	·6796	·6822	·6847	·6873	·6899	·6924	·6950	·6976	4	9	13	17	21
35°	0·7002	·7028	·7054	·7080	·7107	·7133	·7159	·7186	·7212	·7239	4	9	13	18	22
36°	0·7265	·7292	·7319	·7346	·7373	·7400	·7427	·7454	·7481	·7508	5	9	14	18	23
37°	0·7536	·7563	·7590	·7618	·7646	·7673	·7701	·7729	·7757	·7785	5	9	14	18	23
38°	0·7813	·7841	·7869	·7898	·7926	·7954	·7983	·8012	·8040	·8069	5	9	14	19	24
39°	0·8098	·8127	·8156	·8185	·8214	·8243	·8273	·8302	·8332	·8361	5	10	15	20	24
40°	0·8391	·8421	·8451	·8481	·8511	·8541	·8571	·8601	·8632	·8662	5	10	15	20	25
41°	0·8693	·8724	·8754	·8785	·8816	·8847	·8878	·8910	·8941	·8972	5	10	16	21	26
42°	0·9004	·9036	·9067	·9099	·9131	·9163	·9195	·9228	·9260	·9293	5	11	16	21	27
43°	0·9325	·9358	·9391	·9424	·9457	·9490	·9523	·9556	·9590	·9623	6	11	17	22	28
44°	0·9657	·9691	·9725	·9759	·9793	·9827	·9861	·9896	·9930	·9965	6	11	17	23	29

NATURAL TANGENTS.

Angle.	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	1′	2′	3′	4′	5′
45°	1·0000	1·0035	1·0070	1·0105	1·0141	1·0176	1·0212	1·0247	1·0283	1·0319	6	12	18	24	30
46°	1·0355	1·0392	1·0428	1·0464	1·0501	1·0538	1·0575	1·0612	1·0649	1·0686	6	12	18	25	31
47°	1·0724	1·0761	1·0799	1·0837	1·0875	1·0913	1·0951	1·0990	1·1028	1·1067	6	13	19	25	32
48°	1·1106	1·1145	1·1184	1·1224	1·1263	1·1303	1·1343	1·1383	1·1423	1·1463	7	13	20	26	33
49°	1·1504	1·1544	1·1585	1·1626	1·1667	1·1708	1·1750	1·1792	1·1833	1·1875	7	14	21	28	34
50°	1·1918	1·1960	1·2002	1·2045	1·2088	1·2131	1·2174	1·2218	1·2261	1·2305	7	14	22	29	36
51°	1·2349	1·2393	1·2437	1·2482	1·2527	1·2572	1·2617	1·2662	1·2708	1·2753	8	15	23	30	38
52°	1·2799	1·2846	1·2892	1·2938	1·2985	1·3032	1·3079	1·3127	1·3175	1·3222	8	16	24	31	39
53°	1·3270	1·3319	1·3367	1·3416	1·3465	1·3514	1·3564	1·3613	1·3663	1·3713	8	16	25	33	41
54°	1·3764	1·3814	1·3865	1·3916	1·3968	1·4019	1·4071	1·4124	1·4176	1·4229	9	17	26	34	43
55°	1·4281	1·4335	1·4388	1·4442	1·4496	1·4550	1·4605	1·4659	1·4715	1·4770	9	18	27	36	45
56°	1·4826	1·4882	1·4938	1·4994	1·5051	1·5108	1·5166	1·5224	1·5282	1·5340	10	19	29	38	48
57°	1·5399	1·5458	1·5517	1·5577	1·5637	1·5697	1·5757	1·5818	1·5880	1·5941	10	20	30	40	50
58°	1·6003	1·6066	1·6128	1·6191	1·6255	1·6319	1·6383	1·6447	1·6512	1·6577	11	21	32	43	53
59°	1·6643	1·6709	1·6775	1·6842	1·6909	1·6977	1·7045	1·7113	1·7182	1·7251	11	23	34	45	56
60°	1·7321	1·7391	1·7461	1·7532	1·7603	1·7675	1·7747	1·7820	1·7893	1·7966	12	24	36	48	60
61°	1·8040	1·8115	1·8190	1·8265	1·8341	1·8418	1·8495	1·8572	1·8650	1·8728	13	26	38	51	64
62°	1·8807	1·8887	1·8967	1·9047	1·9128	1·9210	1·9292	1·9375	1·9458	1·9542	14	27	41	55	68
63°	1·9626	1·9711	1·9797	1·9883	1·9970	2·0057	2·0145	2·0233	2·0323	2·0413	15	29	44	58	73
64°	2·0503	2·0594	2·0686	2·0778	2·0872	2·0965	2·1060	2·1155	2·1251	2·1348	16	31	47	63	78
65°	2·1445	2·1543	2·1642	2·1742	2·1842	2·1943	2·2045	2·2148	2·2251	2·2355	17	34	51	68	85
66°	2·2460	2·2566	2·2673	2·2781	2·2889	2·2998	2·3109	2·3220	2·3332	2·3445	18	37	55	73	92
67°	2·3559	2·3673	2·3789	2·3906	2·4023	2·4142	2·4262	2·4383	2·4504	2·4627	20	40	60	79	99
68°	2·4751	2·4876	2·5002	2·5129	2·5257	2·5386	2·5517	2·5649	2·5782	2·5916	22	43	65	87	108
69°	2·6051	2·6187	2·6325	2·6464	2·6605	2·6746	2·6889	2·7034	2·7179	2·7326	24	47	71	95	119
70°	2·7475	2·7625	2·7776	2·7929	2·8083	2·8239	2·8397	2·8556	2·8716	2·8878	26	52	78	104	130
71°	2·9042	2·9208	2·9375	2·9544	2·9714	2·9887	3·0061	3·0237	3·0415	3·0595	29	58	87	116	144
72°	3·0777	3·0961	3·1146	3·1334	3·1524	3·1716	3·1910	3·2106	3·2305	3·2506	32	64	96	129	161
73°	3·2709	3·2914	3·3122	3·3332	3·3544	3·3759	3·3977	3·4197	3·4420	3·4646	36	72	108	144	180
74°	3·4874	3·5105	3·5339	3·5576	3·5816	3·6059	3·6305	3·6554	3·6806	3·7062	41	81	122	163	204
75°	3·7321	3·7583	3·7848	3·8118	3·8391	3·8667	3·8947	3·9232	3·9520	3·9812					
76°	4·0108	4·0408	4·0713	4·1022	4·1335	4·1653	4·1976	4·2303	4·2635	4·2972					
77°	4·3315	4·3662	4·4015	4·4374	4·4737	4·5107	4·5483	4·5864	4·6252	4·6646					
78°	4·7046	4·7453	4·7867	4·8288	4·8716	4·9152	4·9594	5·0045	5·0504	5·0970					
79°	5·1446	5·1929	5·2422	5·2924	5·3435	5·3955	5·4486	5·5026	5·5578	5·6140					
80°	5·6713	5·7297	5·7894	5·8502	5·9124	5·9758	6·0405	6·1066	6·1742	6·2432					
81°	6·3138	6·3859	6·4596	6·5350	6·6122	6·6912	6·7720	6·8548	6·9395	7·0264					
82°	7·1154	7·2066	7·3002	7·3962	7·4947	7·5958	7·6996	7·8062	7·9158	8·0285					
83°	8·1443	8·2636	8·3863	8·5126	8·6427	8·7769	8·9152	9·0579	9·2052	9·3572					
84°	9·5144	9·6768	9·8448	10·019	10·199	10·385	10·579	10·780	10·988	11·205					
85°	11·430	11·664	11·909	12·163	12·429	12·706	12·996	13·300	13·617	13·951					
86°	14·301	14·669	15·056	15·464	15·895	16·350	16·832	17·343	17·886	18·464					
87°	19·081	19·740	20·446	21·205	22·022	22·904	23·859	24·898	26·031	27·271					
88°	28·636	30·145	31·821	33·694	35·801	38·188	40·917	44·066	47·740	52·081					
89°	57·290	63·657	71·615	81·847	95·489	114·59	143·24	190·98	286·48	572·96					

Mean differences not sufficiently accurate.

TABLES

CONVERSION TABLES

1 in. = 25·39998 millimetres, usually taken as 25·4.
1 metre = 39·370113 in., usually taken as 39·37 in.
$\frac{1}{1000}$ in. = 0·001 in. = 0·0254 mm.
$\frac{1}{1000}$ mm. = 0·001 mm. = 0·000039 in.
$\frac{1}{100}$ mm. = 0·01 mm. = 0·00039 in.
$\frac{1}{10}$ mm. = 0·1 mm. = 0·00394 in.

MILLIMETRES TO INCHES

mm.	0	10	20	30	40	50	60	70	80	90
0		·39370	0·78740	1·18110	1·57480	1·96851	2·36221	2·75591	3·14961	3·54331
1	·03937	·43307	0·82677	1·22047	1·61417	2·00788	2·40158	2·79528	3·18898	3·58268
2	·07874	·47244	0·86614	1·25984	1·65354	2·04725	2·44095	2·83465	3·22835	3·62205
3	·11811	·51181	0·90551	1·29921	1·69291	2·08662	2·48032	2·87402	3·26772	3·66142
4	·15748	·55118	0·94488	1·33858	1·73228	2·12599	2·51969	2·91339	3·30709	3·70079
5	·19685	·59055	0·98425	1·37795	1·77165	2·16536	2·55906	2·95276	3·34646	3·74016
6	·23622	·62992	1·02362	1·41732	1·81103	2·20473	2·59843	2·99213	3·38583	3·77953
7	·27559	·66929	1·06299	1·45669	1·85040	2·24410	2·63780	3·03150	3·42520	3·81890
8	·31496	·70866	1·10236	1·49606	1·88977	2·28347	2·67717	3·07087	3·46457	3·85827
9	·35433	·74803	1·14173	1·53543	1·92914	2·32284	2·71654	3·11024	3·50394	3·89764

INCHES TO MILLIMETRES

in.	*mm.*	*in.*	*mm.*	*in.*	*mm.*	*in.*	*mm.*	*in.*	*mm.*
$\frac{1}{64}$	0·3969	$\frac{3}{16}$	4·7625	$\frac{15}{32}$	11·9062	$\frac{3}{4}$	19·0500	1	25·4
$\frac{1}{32}$	0·7937	$\frac{7}{32}$	5·5562	$\frac{1}{2}$	12·7000	$\frac{25}{32}$	19·8437	2	50·8
$\frac{3}{64}$	1·1906	$\frac{1}{4}$	6·3500	$\frac{17}{32}$	13·4937	$\frac{13}{16}$	20·6375	3	76·2
$\frac{1}{16}$	1·5875	$\frac{9}{32}$	7·1437	$\frac{9}{16}$	14·2875	$\frac{27}{32}$	21·4312	4	101·6
$\frac{5}{64}$	1·9844	$\frac{5}{16}$	7·9375	$\frac{19}{32}$	15·0812	$\frac{7}{8}$	22·2250	5	127·0
$\frac{3}{32}$	2·3812	$\frac{11}{32}$	8·7312	$\frac{5}{8}$	15·8750	$\frac{29}{32}$	23·0187	6	152·4
$\frac{7}{64}$	2·7781	$\frac{3}{8}$	9·525	$\frac{21}{32}$	16·6687	$\frac{15}{16}$	23·8125	7	177·8
$\frac{1}{8}$	3·1750	$\frac{13}{32}$	10·3187	$\frac{11}{16}$	17·4625	$\frac{31}{32}$	24·6062	8	203·2
$\frac{5}{32}$	3·9687	$\frac{7}{16}$	11·1125	$\frac{23}{32}$	18·2562	$\frac{63}{64}$	25·0031	9	228·6

ANSWERS

EXERCISES ON CHAPTER I

1. (*a*) Feed to stop. (*b*) Face to length. (*c*) Rough turn. (*d*) Finish turn. (*e*) Thread (reduced speed). (*f*) Chamfer and part-off.
2. (*a*) 12 min. (*b*) 16·8 − 12 = 4·8 min.; 80 ft./per min.
3. (i) $\frac{1}{2}$ in. (ii) $\frac{3}{4}$ in. (iii) 1 in. (iv) 2 in. (v) 3 in. (vi) $3\frac{3}{4}$ in. (vii) 19 in.
4. 1,146, 918, 573, 287, 191, 153, 30 r.p.m.
6. (1) Hold in split collet or screwed bush. (2) Thread. (3) Chamfer. (4) Part-off.
7. (*a*) 1·85 min. (*b*) 1·4493, say 1·5 min.
8.

Drill Dia.	$\frac{1}{16}$ in.	$\frac{1}{8}$ in.	$\frac{3}{16}$ in.	$\frac{1}{4}$ in.	$\frac{5}{16}$ in.	$\frac{3}{8}$ in.	$\frac{7}{16}$ in.	$\frac{1}{2}$ in.	$\frac{9}{16}$ in.	$\frac{5}{8}$ in.	$\frac{11}{16}$ in.	$\frac{3}{4}$ in.	$\frac{13}{16}$ in.	$\frac{7}{8}$ in.	$\frac{15}{16}$ in.	1 in.
S = 100 ft./min.	6,100	3,000	2,000	1,520	1,220	1,020	870	760	680	610	550	510	470	430	400	380

9. (*b*) Loading times, $\frac{1}{2}$ min.; drill changes, $\frac{1}{2}$ min.; raise and lower drill spindle, 0·85 min.; total 1·85 min. Fatigue allowance = $12\frac{1}{2}$ per cent. Total time (*a*) 4·11 min. (*b*) 3·7 min.
10.

Drill Dia.	$\frac{1}{16}$ in.	$\frac{1}{4}$ in.	$\frac{1}{2}$ in.	$\frac{3}{4}$ in.	1 in.
40 ft./min. .	2,400	610	306	203	153
60 ft./min. .	3,600	920	460	306	230

EXERCISES ON CHAPTER II

1.

Drill Dia.	0·0625 in.	0·09477 in.	0·1437 in.	0·2180 in.	0·3544 in.	0·5 in.
Nearest Fraction	$\frac{1}{16}$ in.	$\frac{3}{32}$ in.	$\frac{9}{64}$ in.	$\frac{7}{32}$ in.	$\frac{23}{64}$ in.	$\frac{1}{2}$ in.
Spindle r.p.m.	5,490	3,620	2,386	1,573	1,038	684

2.

Drill Dia.	0·0625 in.	0·09477 in.	0·1437 in.	0·2180 in.	0·3544 in.	0·5 in.
Nearest Fraction	$\frac{1}{16}$ in.	$\frac{3}{32}$ in.	$\frac{9}{64}$ in.	$\frac{7}{32}$ in.	$\frac{25}{64}$ in.	$\frac{1}{2}$ in.
Spindle r.p.m.	15,270	10,080	6,649	4,387	2,895	1,910

3. Speeds in Arithmetic Progression are : 5,490, 4,529, 3,567, 2,606, 1,645, 684 r.p.m.
4. 255·9 min. or $4\frac{1}{4}$ hours approximately.
5. $S = 117$ ft./min.
6. (*a*) 603·4 lb. (*b*) 215·5 tons/in.^{2}
7. Depth of cut = 0·1835 in. or $\frac{3}{16}$ in. approximately. Tangential force = 415 lb.
8. 205 ft./min.
9. $\theta = 4° 48'$; top-rake angle = 24° 48′ ; clearance = 3° 12′.
10. Top-rake angle = 15° 12′ ; clearance angle = 12° 48′.
11. (*a*) 0·2088 in., say 0·21 in. approx. (*b*) 0·513 in. below centre.

EXERCISES ON CHAPTER III

6. Operations from square toolpost: forming, turning, chamfering, parting off.
7. Hold in hexagonal jaws ; feed to stop ; turn down (roller box) ; chamfer end ; thread using diehead ; face bolt head ; part off and radius or chamfer at 30°.

EXERCISES ON CHAPTER IV

2. (*a*) 0·00096 in. (*b*) 131 r.p.m. (*c*) 2,096. (*d*) 0·65 in.
3. (*a*) 0·4 cu. in./min. (*b*) 0·6 cu. in./h.p. (*c*) 4 min.
4. (*a*) 1·75 ($1\frac{3}{4}$). (*b*) 481 lb.
6. (*a*) 1 hole in 15 circle $\frac{\text{24 spindle gear}}{\text{72 wormgear}}$. (*b*) 2 holes in 33 circle $\frac{72}{24} \times \frac{40}{32}$. (*c*) 1 hole in 16 circle $\frac{64}{28} \times \frac{56}{24}$. (*d*) 1 hole in 17 plate $\frac{68}{48} \times \frac{32}{56}$.
8. $\frac{40\,C\,D}{ND - nC}$ per turn of crank.
9. (*a*) 9°, i.e. ($\frac{360}{40}$). (*b*) $4\frac{1}{2}$°, i.e. ($\frac{9}{18} \times \frac{360}{40}$). (*c*) 25° 43′.
10. $\frac{64}{40} \times \frac{100}{44}$ gears and 1 hole in 33 circle, $\frac{1}{4}$°.
12. (*a*) (i) 8 holes in 20 circle, $\frac{72}{24} \times \frac{40}{48}$; (ii) $\frac{11}{33}$ and $\frac{24}{56}$; (iii) $\frac{6}{20}$ and $\frac{40}{28}$; (iv) $\frac{6}{27}$ or $\frac{4}{18}$ and $\frac{72}{24} \times \frac{48}{32}$.
(*b*) (i) $\frac{20}{49}$ and $\frac{56}{48} \times \frac{28}{40}$; (ii) $\frac{8}{24}$ and $\frac{24}{56}$; (iii) $\frac{8}{28}$ and $\frac{28}{72}$; (iv) $\frac{12}{54}$ and $\frac{24}{48}$. (i.e. 12 holes 54 circle + $\frac{24T}{48T}$ gear).
13. (*a*) $1\frac{3}{27}$ or $1\frac{2}{18}$ turns (36 divisions) ; $2\frac{6}{27}$ or $2\frac{4}{18}$; $\frac{64}{40} \times \frac{100}{44}$ and $\frac{1}{33}$. (*b*) 2 turns any plate ; 2 holes 66 plate and $\frac{64}{40} \times \frac{100}{44}$; 6 holes 54 circle.
14. Lead = 3·459 in.; set head to 43° 46′, gear ratio of 2 : 1.
16. (*a*) 0·01 in. (*b*) 0·0025 in.
17. 51 lb.
18. 204 lb

EXERCISES ON CHAPTER V

5. (*b*) Feed $F = \pi DN \sin \theta$.
6. (*a*) 142 ft./min. (*b*) 276 ft./min. (*c*) $38\frac{1}{2}$ ft./min.
8. (*a*) Setting $h = 0{\cdot}110$ in. (*b*) $h = 0{\cdot}154$ in.

EXERCISES ON CHAPTER VI

1. (*a*) $\frac{20}{30} \times \frac{100}{50}$. (*b*) $\frac{40}{100}$. (*c*) 40 : 45.
2. (*a*) $\frac{20}{100} \times \frac{25}{50}$. (*b*) $\frac{20}{40}$.
3. (*a*) $\frac{40}{50}$. (*b*) $\frac{20}{40}$ or $\frac{40}{80}$.
4. (*a*) $\frac{127}{120}$. (*b*) $\frac{127}{120} \times \frac{30}{60}$.
5. (*a*) $\frac{50}{127}$. (*b*) $\frac{120}{127}$.
6. Leading angle = 74° 45′; 102° or 99° with clearance.
14. Tan $A = \frac{CN}{\pi D}$, when $N = 4$ speed of cutter = cam speed.
15. Relief angle = 1° 49′, camshaft makes $\frac{60}{4} = 15$ r.p.m., spindle $3\frac{3}{4}$.
16. 2° 21′.
17. (*b*) 288 r.p.m. for work, 576 r.p.m. for cutter.

EXERCISES ON CHAPTER VII

4. (*a*) $\frac{\text{Cutting time}}{\text{Return time}} = \frac{220}{140} = 1{\cdot}57 : 1$. (*b*) $\frac{14}{45}$ or $\frac{1}{3}$ sec.; $\frac{22}{45}$ or $\frac{1}{2}$ sec.
5. $\frac{1}{N_n} = \frac{1}{250}'' = \frac{4}{1000} = 0{\cdot}004$ in.
9. (*a*) 100 ft./min. for H.S.S.; 40 ft./min. for carbon-steel drills. (*b*) 0·006 in. per rev. $\frac{1}{4}$-in. drill; 0·010 in. per rev. $\frac{1}{2}$-in. drill, and 0·014 in. per rev. 1-in. drill. (*c*) 1,520 H.S.S. drill, 610 carbon-steel; 760 and 306; 380 and 153 r.p.m.

EXERCISES ON CHAPTER IX

3. $1\frac{1}{2}$ in., 1 in., and $\frac{1}{2}$ in. (1·5000, 1·0000, 0·5000).
4. Vertical co-ordinate = 1·5025 in.
   Horizontal co-ordinate = 2·82528 and 1·51472 in.
   Check: 2·82528 + 1·51472 = 4·34000 in. = base of triangle.
5. Horizontal co-ordinate = 0·58595 in.
   Vertical co-ordinate = 0·68965 and 0·81035.
   Check: 0·68965 + 0·81035 = 1·5000 in. = side *c* of triangle.

EXERCISES ON CHAPTER X

3. $\mu = 0{\cdot}0138$; friction h.p = 1·2.
5. 142·4 gal. per hour
7. 0·000422 in./side = 0·000844 in.
8. 0·00056 in./side = 0·00112 in.
9. 0 00075 in./side = 0·0015 in. in diameter.
10. 0·000598 in./side = 0·001196 in. Diameter of shaft = 2·001196, say 2·0012 in.

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